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Optimization Programming for Stormwater Control Measures: Methods for Sizing and Selection

Author
Mir Mohammad Sadeghi, Majid Kazem

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Optimization Programming for Stormwater Control Measures: Methods for Sizing and Selection

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requirements for the degree Doctor of Philosophy

in Geography

by

Kazem Mir Mohamad Sadeghi

Committee in charge:

Professor Hugo A. Loáiciga, Chair

Professor Edward Keller

Professor Christina Tague

Dr. Shahram Kharaghani

June 2015

The dissertation of Kazem Mir Mohamad Sadeghi is approved.

Edward Keller

Christina Tague

Shahram Kharaghani

Hugo A. Loáiciga, Committee Chair

May 2015

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VITA

Kazem Mir Mohamad Sadeghi

EXPERIENCE SUMMARY:

Have many years of civil and environmental engineering and consulting experience, including hazardous waste management, pollution prevention assessments, and design of industrial wastewater pretreatment facilities and gas collection/treatment systems. Knowledgeable in water quality, wastewater, and hazardous waste regulations and have represented industries in regulatory negotiations, the preparation of various civil and environmental engineering designs, compliance reports, as well as local, state, and federal permits. Designs of building with plans and civil engineering designs, project for concrete and asphalt in construction. Assisted in development of stormwater pollution prevention plans, Low Impact Development, rainwater harvesting, EIR/EIS reports, and petroleum contaminated groundwater recovery program. 26 reviewed journal publications, 3 U.S.A. patents, 1 Canadian patent, and 1 International patent and 14 presentations at international conferences.

EDUCATION:

Engineer Degree, Civil Engineering
University of Southern California
Los Angeles, CA December 1989.

Master of Science, Environmental Engineering
University of Southern California
Los Angeles, CA December 1987.

Bachelor of Science, Chemistry
University of California, Santa Barbara
Santa Barbara, CA December 1985.

PROFESSIONAL ENGINEER: California Registered Civil Engineer (C-69913)

TRAINING:

Engineer-In-Training in State of California.
ETAC 40-Hour Hazardous Waste Workers Training.
Alameda Corridor Transportation Authority Roadway Worker Training

PROFESSIONAL AFFILIATION: American Public Works Association, Member.
Heal the Bay.
Sigma Xi, Member.
American Society of Civil Engineers, National, Member.

ACTIVITIES: Private Pilot License.
Brown Belt in Kempo Karate.

EXPERIENCES: Environmental Engineering Associate, City of Los Angeles, June 2002 to Present:

As a Environmental Engineering Associate for the City of Los Angels, I have been responsible for a wide range of civil and environmental engineering tasks for the Department of Public Works. I have been working for the Permitting section of Industrial Waste Management Division. The different projects include the Dental Offices programs, LIU and SIU permitting of Industries for the City of Los Angeles. In addition, I have worked in the Watershed Protection Division for the TMDL Implementation Plan and Green Infrastructure for stormwater runoff in the City of Los Angeles.

Associate Environmental Engineer, Parsons Corporation, April 1999 to June 2002.

I have been assigned to the Metro Rail Project (Los Angeles Metropolitan Transportation Authority) since April 1999 and have provided technical support on various civil and environmental tasks during the construction of Segments 2 and 3 of the Project (Parsons-Dillingham and ENO25 Contract). My responsibilities include civil engineering tasks, environmental compliance monitoring/sampling, report preparation, data analysis, interactions with the Resident Engineers, contractors/subcontractors, and MTA staff, attending construction meetings, oversight and monitoring.

I have also been involved with the ACTA Project (Alameda Corridor Transportation Authority) since July 1999. I have served this Project in various capacities, from providing water, air, and soil quality monitoring support and organizing/implementing environmental monitoring programs for the Project. My versatility, communication skills and professionalism with the contractors/subcontractors and regulatory agencies have been a great asset to this ACTA Project.

I have also been involved with Telecommunication program manage re-signage of Verizon Buildings since June 2000. Bell Atlantic/GTE have a merger that has result in the newly formed Verizon Corporation. Such a merger means that the buildings to be re-signed are scattered throughout the United States, including Alaska and Hawaii. I am Regional Coordinator for the Western section of the Verizon Signage Program with over 600 sites. Responsibilities for building size measurements and survey, signs installation designs, include field survey, work order to vendor, execution, documentation, and invoices.

I have also been involved with the City of LA NOS-ECIS Project (North Outfall Sewer – East Central Interceptor Sewer) since August 2001. I have served this Project in various capacities, from providing water, air, and soil quality monitoring support and implementing environmental monitoring tasks for this City of LA Project. I have worked in this project for the mining and tunneling and have monitored several gases using different instrumentation. I have also collected air gases from the tunnel during ECIS construction for lab analysis and performed QA/QC for health and safety.

EXPERIENCES:

Graduate Student, University of California, Santa Barbara, September 2009 to June 2015.

Project Engineer, Sedcon Engineers, Contractors, Inc., August 1993 to October 1998.

Research Assistant, Civil Engineering Department, University of Southern California, January 1986 to December 1992.

Project Engineer, Western Extraction Technology, Inc., August 1983 to December 1998.

Project Engineer, Alton Geoscience, Inc., September 1990 to August 1991.

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ABSTRACT

Optimization Programming for Stormwater Control Measures:

Methods for Sizing and Selection

by

Kazem Mir Mohamad Sadeghi

The Study Problem and Research Objectives. Fouling of water quality in receiving urban storm runoff is chronic in metropolitan areas across the USA and large cities worldwide. These urban areas have well-known problems of polluted storm runoff and urban flooding. Urban storm runoff exhibits deleterious physical-chemical-biological characteristics, such as bacteria, trash content, large biochemical-oxygen-demand (BOD), oil & grease, toxic sediments, water-borne pathogens, suspended solids (SS) and total dissolved solids (TDS), heavy metals, and nutrient content that degrade water quality of receiving waters. The contamination of urban runoff is the result of a number of natural and anthropogenic processes: changing and rapid expanding population and land use within urban areas; vulnerable receiving water bodies that become contaminated from degraded storm runoff that hinders their hydrologic, ecologic, and socioeconomic functions, and intense rainfall events with pronounced seasonal and inter-annual variability of storm intensity (typical in the western United States). State and federal regulations on Total Maximum Daily Loads (TMDLs) of pollutants to natural waters from urban storm runoff are not met by most cities in the USA. This thesis presents a modeling and experimental study using one of the best available data sets on urban land use, soils, groundwater, streets,

storm conveyance infrastructure, non-point and point sources of pollution, rainfall, and Stormwater Control Measures (SCMs) technologies. This thesis proposes a novel approach to (1) model, screen and or evaluate urban areas using Geographic Information Systems (GIS) with the purpose of selecting appropriate SCMs in watershed hot spots, (2) select suitable SCMs to be deployed for the capture of and treatment or retention of urban runoff using Optimization Programming, (3) implement and test the proposed research in a large urban area with pervasive urban runoff pollution, and (4) field test SCMs for which there is limited or no information on treatment efficiency to assess their runoff-cleaning potential. Optimization methods are developed and presented in this research work to minimize the total cost of SCM deployment while satisfying constraints on (i) the total cost of deployment, (ii) SCM capacities, (iii) volumetric balance at SCM sites, (iv) stormwater volumes at arbitrary sites, (v) unit Operational, Maintenance, and Replacement (OMR) cost, and (vi) water-quality and quantity at monitoring locations. Two alternative optimization models for SCM siting and sizing are presented in this thesis:

- ***Linear Programming (LP)*** for optimal sizing of SCMs relies with a linear programming formulation. In addition, the Binary Linear Integer Programming (BLIP) for optimal selection of SCMs based on a binary (0,1) linear integer programming formulation.
- ***Nonlinear Programming (NLP)*** for optimal sizing and selection of SCMs uses mixed (binary-real) nonlinear integer programming formulation.

Summary of the Research Method. The key tasks accomplished in this thesis are:

- Modeling and determination of priority catchments for SCM deployment based on SCM;
- Development and application of a SCM Optimization programing model to select from within the GIS-evaluated SCMs those that are most cost effective in reducing the pollutant loads and concentration in urban runoff;
- Nonlinear model's results have been field tested by implementing its SCMs selection with site-specific data;
- Conducted field experiment to evaluate the pollution removal efficiency of percolation wells and vegetated swales.

The implementation of GIS-based electronic maps to classify areas according to their conditions: heavy traffic, impervious soils, high rainfall intensity for design storms, high urban density, and steep topography. The selected SCMs are tested in chosen priority catchments to assess model-predicted performance with field performance. The research task consists of field-experimenting with dry wells and vegetated swales. These types of SCMs appear to have good performance potential in permeable soils, and swales exhibits high aesthetic distinction and value. These SCMs are field tested to determine their pollutant removal efficiency for selected indicator pollutants (for example, total suspended solids).

Broad Impacts of the Proposed Research. This thesis overarching hypothesis is that the sequential application of (1) computer based modeling in screening of high priority urban catchments and cost effective SCMs, and (2) optimization programming, can be used successfully in (i) identifying catchments with high SCM indices to urban runoff pollution and (ii) selecting the most cost-effective SCMs to reduce runoff pollution. This novel research concept represents a trend setting approach in combating urban runoff pollution in the United States, and in other places where the resources and know-how for urban runoff pollution control are in high demand and required.

Intellectual Merit of the Research. This is a novel research attempt to develop and integrate novel analysis of pollution and suitability for SCM deployment with optimization programming method for the selection of the types and sizes of SCMs in urban catchments.

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1. INTRODUCTION: BACKGROUND, PROBLEM STATEMENT, AND PREVIOUS PERTINENT WORK

1.1 Background

Urban runoff is a major source of water-quality degradation in cities across the USA that discharge storm runoff to rivers, lakes, streams, seas, wetlands and aquifers, which serve natural and socioeconomic functions. Fowling of water quality in water bodies receiving urban storm runoff is chronic in metropolitan areas across the USA and big cities are examples of urban areas with well-known problems of polluted storm runoff. Urban runoff from storms exhibits deleterious physical-chemical-biological characteristics, large biochemical-oxygen-demand, oil & grease, water-borne pathogens, suspended and total dissolved solids, trash, heavy metals, and nutrient content that degrade water quality of receiving waters. The contamination of urban runoff is the sum of a number of natural and anthropogenic processes: rainfall affected by changing precipitation patterns amidst pronounced seasonal and inter-annual variability of storm intensity; changing and expanding population and land use within urban areas; vulnerable receiving water bodies that become contaminated with degraded storm runoff that hinders their hydrologic, ecologic, and socioeconomic functions. State and federal regulations on Total Maximum Daily Loads (TMDLs) of pollutants to natural waters ways from urban stormwater runoff are not met by many cities and counties in the United States of America (USA).

Most of the United States' urban areas have separate stormwater and wastewater collection systems. The wastewater discharge is directed to treatment facilities and stormwater with all its pollutants that it collects in its path is discharged untreated into nearby waterbodies. There are many different constituents that cause impairments to urban water bodies. They typically affect aquatic life, recreational use, water supply or human wildlife consumption. Despite the fact that these constituents are numerous, they can be grouped into a select number of categories that describes their sources or impact (Walsh et al. 2005; Kaye et al. 2006). For example The City of Los Angeles (City) has identified the pollutants of concern for the local watersheds and these pollutants can be grouped in the following categories (City of Los Angeles 2009A, 2009B):

- **Trash -** Trash is a stormwater pollutant consisting of improperly discarded waste materials that can find its way to waterbodies such as beaches, harbors, creeks, rivers and lakes.
- **Heavy Metals -** Many of these studies identify heavy metal generation as being derived from automobile activities.
- **Oil and Grease -** Another pollutant that is discharged by automobiles is oil and grease (O&G) and in stormwater is predominantly petroleum-related oil.
- **Pesticides -** Pesticides applied in residential gardens and public parks throughout the watershed constitute a major stormwater pollution.
- **Nutrients -** The primary source of nutrients into local waterbodies are point sources from sewage treatment plants.
- **Bacteria -** Bacterial pollution in stormwater is usually measured through total and fecal coliform and enterococcus counts. Despite a huge amount of research conducted, the breakdown of sources of bacterial pollution remains to certain extend unexplainable.

The most common pollutants causing impairments include: trash, metals, coliform, bacteria, oil and grease, nutrients, and toxic organic compounds, such as pesticides and herbicides. These pollutants come from many sources, and are found in the water column, or are deposited in sediments and fish tissues. Understanding pollutant sources is critical to improving water quality. If the source can be reduced or eliminated, water quality benefits can be more quickly realized with lower cost. These groups of pollutants are a reflection of the watershed's activities. Urban watersheds are comprised of transportation corridors, housing estates, recreational areas, and business and commercial strips. The various pollutants can be related to urban activities or to the physical characteristics of the watershed. In fact, the bulk of stormwater pollution can be attributed to a limited number of human activities, use of consumer products, or watershed characteristics. The watersheds are characteristics, needs, and opportunities that require specific approaches and solutions. These watersheds comprise many urban areas that share responsibility for meeting water quality regulations. Jurisdictional coordination is key to successful urban runoff management on a watershed-wide basis.

For decades the focus of urban waste management has been on collecting, treating and disposing of wastewater and solid waste, because of their instantaneous and theoretically large impacts on public health. Stormwater management is a relatively new development (compared to wastewater) and initiated by the federal Clean Water Act and its successive amendments in the 1970's and 1980's. Under this Act, urban runoff must meet National Pollutant Discharge Elimination System (NPDES) Permit requirements, which are designed to reduce pollutants carried in stormwater from point sources. Pollutants carried by stormwater can have substantial impacts on water quality, aquatic ecosystems and public health. To address these concerns and to remain acquiescent with NPDES requirements, many cities in the United States (USA) have developed stormwater management programs. Even with these programs in place, stormwater pollutants can still seriously impact water quality. Where the impact is significant, Total Maximum Daily Loads (TMDLs) are established to set limits to the amount of pollutants that a specific water body can receive and still meet water quality standards.

Twenty two of TMDLs have been adopted in the City of Los Angeles area (the City); adoption of more TMDLs is expected in the near future. As a result, the need to enhance the City's urban runoff management program has become more crucial because of approaching regulatory deadlines to meet TMDL requirements that will eventually be integrated into the national pollution discharge elimination (NPDES) Permit for the Municipal Separate Storm Sewer System (MS4). As with many cities across the USA, in response to Clean Water Act regulatory mandates, the City of Los Angeles started its Watershed Protection Program (formerly named Stormwater Program) in 1990 through Los Angeles Sanitation, Department of Public Works. The Watershed Protection Division, which is responsible for this program, has been tasked with the following to meet its TMDL:

- Satisfying federal, state, regional, and local regulatory requirements;
- Coordinating City programs to minimize polluted runoff;
- Optimizing beneficial use of beaches and receiving waters by reducing pollutant loads through watershed management;
- Reducing waste disposal by providing public and employee education programs;
- Improving the waste disposal infrastructure;

- Expanding the use of technical knowledge regarding urban runoff issues; and
- Minimizing the adverse effects of flooding on the City of Los Angeles.

While the City is one of the nation's leaders in urban runoff management, the approach might best be described as reactive to specific problems. Planning efforts have been done in a partly integrated and localized manner, but not on a watershed wide basis. This approach has resulted in the development and implementation of a variety of stormwater programs and projects, including public outreach and education, inspection, enforcement, scientific studies and construction of SCMs. For these TMDL requirements, the City started the SUSMP (Standard Urban Stormwater Mitigation Plan) program in the 1990s (City of Los Angeles 2009E). Then in 2012 the City Council adopted the Low Impact Development (LID) plan which was the first for a big city in the USA for meeting the TMDLs and helping in the climate changes for the City (City of Los Angeles, 2011). A new permit was issued to the City by the State of California for the NPDES (California Regional Water Quality Control Board 2012).

1.2 Control Strategies – Structural Controls

Structural controls are systems deployed to interact with stormwater runoff to prevent the discharge of pollutants to waterbodies. These systems include examples such as catch basins or green roof runoff to capture and treat pollutants. These systems include the following structural controls:

- **Hydrodynamic Separation Technology** - Hydrodynamic Separators such as Continuous Deflective Separation (CDS) units are considered by the U.S. Environmental Protection Agency (USEPA) as full capture systems if designed to treat the one-year storm. The use of "full-capture" devices such as CDS on the existing storm drain system is very restrictive as concluded by feasibility studies and widespread installation of full capture devices, including hydrodynamic devices in existing storm drain outlets, is not feasible (City of Los Angeles, 2002). One additional constraint is the relative high capital cost of installation. Limited application on a case-by-case basis in high trash generation areas may be considered in small drains, but limitations related to constructability and operability would also need to be addressed. Mechanical filtration devices can remove pollutants such as debris, sediment, oil & grease from stormwater runoff.

- **Netting Systems** - This can also be designed to meet the "full-capture" definition and these systems, similarly to the CDS units, can introduce significant head losses. The high maintenance constraint of full capture systems applies to netting systems. Their installation may be considered on a limited basis for storm drains in high trash generation areas.
- **Percolation Well (dry well)** - Percolation wells are effective stormwater control measures (SCM) for locations with deep groundwater and permeable soils with high infiltration capacity. Percolation wells must be separated a sufficient distance with respect to other SCM to have achieve high infiltration of stormwater. In addition, percolations wells must be maintained to remove trash and sediments before the next storm event.
- **Catch Basin Screens and Inserts** - Catch basin screens and inserts are designed to trap all trash greater than the screen size, provided that they have large storage volumes and are properly maintained. The maintenance will be different from

location to location and this will determine their effectiveness\required cleaning frequency. The inserts are made of galvanized steel (this way other metals will not inter the waterways). A solution for flooding is the use of covers employing different devices (i.e., magnets, counter-balance troughs, etc.) that allows them to open when water builds up behind the screen. This concept allows the cover to open to relieve local flooding conditions and then close.

- **Grassy Swale (vegetated swale/planter boxes)** – Swales are designed to convey and treat shallow flow or sheet flow runoff. They are often thickly vegetated, uniformly graded areas that intercept sheet runoff from impervious surfaces such as parking lots, roadways, and rooftops. Swales are designed to slowly convey stormwater runoff and in the process trap pollutants, promote biofiltration, and reduce flow velocities. Swales must maintain/healthy vegetation growth for biofiltration to be effective. In addition, they must be maintained to remove trash and sediments before the next storm event.
- **Pervious Pavement/Asphalt** – Pervious (permeable) pavement/asphalt contain small voids that allow stormwater to pass through to the base. They come in a variety of forms; they may be a modular paving system (concrete pavers, modular grass or gravel grids) or poured-in-place pavement (porous concrete, permeable asphalt). All permeable pavements with a stone reservoir base treat stormwater and remove sediments and metals to some degree by allowing stormwater to percolate through the pavement and enter the soil below.
- **Rain Cisterns (detention basin/rain barrels)** – Rain cisterns are effective SCMs and are good system to capture and reuse stormwater. Rain cisterns (detention

basin/rain barrels) store rainwater from roofs and other impervious surface flows for reuse in landscape irrigation. Rain cisterns (detention basin/rain barrels) are containers typically made of a heavy duty metals or plastic. For detention basin the range can be from 100s gallons (1 gallon = 3.785 liters) to 1,000s gallons. Rain barrels range in size from the standard 55 gallons to more than 80 gallons. Eco-friendly rain barrels assembled from recycled food barrels or manufactured from recycled plastics are available. Rain cisterns (barrels) must have a roof for gravity flow and the underground system may be expensive to install. They must be regularly maintained to remove leafs and sediments.

- **Infiltration System** – The infiltration system is an effective SCM for locations with deep groundwater and high infiltration rates. Infiltration systems must have a pre-treatment system to assure lasting high infiltration rates in the system. In addition, trash and sediments must be removed after each major storm event.

1.3 Institutional Controls

Institutional controls and operations discourage the generation of pollutants (e.g., trash, oil & grease, bacteria, etc…) streets, sidewalks, alleys, and catch basins. These institutional and operations controls are employed to optimized their effectiveness and help educate the public about stormwater pollutants. This section provides a description of these institutional controls measures and examples from City of Los Angeles:

- **Anti-littering Enforcement** – The statutes of anti-littering forbid littering in public areas (right-a-ways, sidewalks, alleys, parks, beaches, roads, rivers, lakes, etc…). Many agencies are responsible for enforcing these requirements. For example, the

City of Los Angeles Police Department is the leading entity in enforcing the Los Angeles Municipal Code's (LAMC) requirements for anti-littering.. However, other entities such as the Department of Public Works and the Department of Recreation & Parks also deploy inspectors to prevent littering along City of Los Angeles streets and public parks, respectively.

- **Street Sweeping** – A very effective method to remove pollutants is by street sweeping before rain events. This is accomplished almost exclusively using motorized sweepers to sweep streets and municipal parking lots. The frequency of sweeping varies from daily for selected commercial strips to monthly for the least urbanized portions. The presence of known areas with visible trash is one of the criteria that the agencies use to determine street- sweeping frequency.
- **Catch Basin Cleaning** – Another effective method is conducted by agencies like public works maintenance crews. Catch basins are typically inspected once a year and any trash found is removed. Catch basins cleaning increases with the frequency of heavy storm events and heightened trash and sediment accumulation after rain events.
- **Abandoned Trash** – Abandoned trash is reported to hotlines and fro examples maintained by the Los Angeles Public Works Department. Pick-ups are conducted for trash and bulky items that would otherwise be left on the streets and alleys and ultimately reach waterways via stormwater transport.
- **Trash Containers** – These are maintained by Public Works and have reduced the amount of illicit trash along selected commercial strips. Their effectiveness is dependent on placement location within the City streets.

- **Educational Anti-Littering Outreach –** These efforts have only recently been emphasized and currently are limited to the stormwater program's anti-pollution public education. Citizens are also discouraged to illicitly dispose trash through postings, signs, and billboards, television and radio advertisement, internets (website – blog, facebook, twitter, etc.). These efforts have generally been citywide and not targeted to high- trash generation areas. Future efforts will be targeted to areas known for high trash generation.
- **Community Clean-Up Programs –** The City of Los Angeles' Operation Healthy Neighborhoods directed by the Mayor's Office or the Operation Clean Sweep by the Department of Public Works have encouraged trash clean-up and litter reduction. These programs involve partnerships between the City, community activists, and volunteers to beautify the most affected communities. These efforts in the community help to reduce trash and pollutants discharged into neighborhoods and eventually into waterways.

1.4 Problem Statement & Previous Pertinent Work

This thesis presents novel mathematical models for the sizing and placement of stormwater control measures (SCMs) with the objectives of reducing urban flooding and improving urban stormwater quality. The models constitute a new method for integrated urban stormwater management. SCM is herein used synonymously to the term best management practice, or BMP, which is commonly used in the technical literature. The term SCM embodies the name of its subject matter "stormwater", thus its appeal and increasing acceptance (California Regional Water Quality Control Board, 2014).

The models for SCMs sizing and placement minimize the total cost of SCM implementation, and account for the conservation of stormwater mass and pollutants' masses in the formulation of constraints that assure physical feasibility while meeting stormwater retention and purification requirements. This thesis relies on stormwater, SCMs, hydrologic, and soils data gathered in the City of Los Angeles (City) to demonstrate the applicability of the developed models for SCM optimization. The SCM sizing and placement models are, however, of general applicability to any urban region beset by stormwater management challenges.

The models for SCMs sizing and placement herein developed and tested include linear programming (LP) and nonlinear programming (NLP) versions. LP model formulations take the following general form:

Minimize $\boldsymbol{b}^T\boldsymbol{x} + c$ (1.1)

Subject to $A\,\boldsymbol{x} \leq \boldsymbol{d}$ (1.2)

Equation (1.1) represents the objective function, that is, the minimization of the total cost of SCMs implementation. The vectors $\boldsymbol{b}$ and $\boldsymbol{x}$ represent the vector of variable costs and the vector of decision variables, respectively. The coefficient c in equation (1.1) represents the fixed cost of SCM implementation, not related to the size of the SCMs. It accounts for costs incurred for stormwater management independent of the size and number of SCMs (acquisition of right of ways, for example). The vector of decision variables $\mathbf{x}$ includes the unknown sizes of the SCMs, which are positive, real quantities, and binary variables that take the value of either 0 or 1, the former occurring when an SCM is not deployed at a specific location where a SCM could be deployed, and the latter occurring when an SCM is deployed at a site selected for possible SCM deployment. The minimization of equation (1.1) is achieved by finding the optimal values of the decision variables **x**. Equation (1.2) is the set of constraints imposed on the decision variables **x**. The known matrix A represents a matrix of constraints coefficients that reflect the costs of SCM deployment and achieve meet water-retention and stormwater-purification requirements. The matrix A incorporates all the physical-economic coefficients imposed on the vector of decision variables. The vector **d** represents a known vector of constraint coefficients. A full explanation and application of the LP equations (1.1) and (1.2) can be found in Chapter 4.

The NLP model formulation of SCMs sizing and placement takes the following form:

Minimize $g(\boldsymbol{x})$ (1.3)

Subject to:

$f_i(\boldsymbol{x}) \leq b_i \qquad i = 1, 2, \ldots, M$ (1.4)

In equation (1.3) g(**x**) represents a nonlinear cost function imposed on the vector of decision variables. The constraints imposed on the decision variables are captured by equation (1.4), There are M constraints, where M is as large as needed to fully describe all the requirements imposed on SCMs. Some of the constraints (1.4) may be linear, while others are nonlinear. The NLP model is presented in full in Chapter 5.

Much research on storm runoff (water quality, hydrology, climate change, rainfall, land use, modeling, etc.) has been done in the United States, especially after the 1972 enactment of the federal Clean Water Act and followed by revisions in Clean Water Act 1977, 1981, and 1987 (USEPA 1972; Novotny and Olem 1994; Clark et al., 1996, 2005; Wong et al. 1997; Singh and Woolhiser 2002; California Stormwater Quality Association 2003; Beven 2004; Grimm et al., 2008; Faustini et al., 2009, Hagekhalil et al., 2014). The Clean Water Act issued regulations to maintain the quality of the waters of the United

States. One regulatory mechanism is through the setting of TMDLs, which, in turn, has given rise to a multi-billion dollars industry of SCMs and treatment technologies nationwide (Whitman, 2000; Davis, 2005; Green 2007; City of Los Angeles 2009A, 2009B, 2009C). In this respect, the National Pollutant Discharge Elimination System (NPDES) (Clean Water Act, Section 402) has had an enormous impact on the deployment of storm-runoff management technologies. The NPDES requires that permits be obtained for point-source discharges to surface waters (including storm drains) under the jurisdiction of the Clean Water Act. The body of technical publications in the field of storm runoff, impaired water quality, SCMs, Low Impact Development (LIDs), and TMDLs is very large and has been studied recently in detail (Jefferies et al, 1999; see a review in City of Los Angeles 2009A, 2011; Faucette, 2010; Beyerlein, 2012, Lee et al., 2012). Sustainable approach to LID SCMs designed to enhance the retention of stormwater runoff and pollutants in vegetation, soils, and aquifers, thus minimizing output to streams, wetland, lakes, or the sea have been studied in the past. These SCMs are of the storage/infiltration type. The old SCM paradigm relied mostly on channelized SCMs to capture storm runoff in drains and ditches and rapidly conveying it to impacted waters (Faucette, 2010).

The microbial pollution of recreational freshwater (Loáiciga, 2001) and the pollution of recreational coastal seawater by contaminated streams (Loáiciga and Leipnik, 2005) have been studied, in addition to studies relating precipitation to runoff in human-impacted watersheds (see Loáiciga, 2002, 2008; McMichael et al., 2005). The hydrologic monitoring and the statistical analysis of stationarity and trends in hydrologic time series are given in American Society of Civil Engineers (2003) and other research relates to the interactions between climate, aquifer characteristics, and topography that control the recharge to aquifers in sloping terrain (Loáiciga, 2005; Loáiciga, 2009). The latter research is relevant to SCMs that rely on the subsurface as a retention reservoir for storm runoff.

The United States Environmental Protection Agency (USEPA, 1997) presented a methodology for the calculation of TMDLs. The investment in storm runoff technologies (structural or non-structural) is a complex resource allocation problem: targets for water quality in receiving water must be met. There are multiple SCMs and other storm-runoff management technologies (storm drains, treatment plants, reservoirs) available to achieve this goal. There is, however, a cost involved in implementing, maintaining, and replacing storm-runoff management technologies. In addition, sources of pollutants are geographically distributed, and the number of deployed technologies must be such that geographical coverage is sufficient to capture and retain enough storm runoff and pollutants to meet TMDL targets (USEPA 2003, 2004, 2007). The Federal Clean Water Act (CWA) provided the basis for the protection of water quality in fresh and marine waters. Water quality regulations applicable to urban runoff management are primarily implemented through the National Pollutant Discharge Elimination System Permit for the Municipal Separate Storm Sewer System (NPDES MS4 Permit). Earlier versions of the NPDES MS4 Permit were mostly narrative with requirements for implementation of Best Management Practices. Future NPDES MS4 Permits, however, are likely to also include numeric water quality standards, or action levels, and pollutant load allocations that are specified in Total Maximum Daily Loads (TMDLs). A TMDL establishes the maximum amount of a pollutant that a waterbody can receive from all sources, including the MS4, while still meeting water quality goals.

A benefit/cost analysis of stormwater improvements was reported by Kalman et al. (2000). The cost estimates for storm runoff control technologies produced by Currier et al. (2005) shows low-range and high-range benefits from investment in stormwater quality improvement in the City of Los Angeles. The analysis shows that an $8 billion dollar investment (2005 value) would produce a present value of benefits that ranges from $46 billion to $178 billion (Currier et al 2005), discounting over a 30-year period. Currie et al. (2005) stated that enhanced urban aesthetics, ecosystem improvement, increase in property values, and groundwater savings are primary contributors to benefits to be realized from investments made to improve stormwater quality in the Los Angeles region. The implication this benefit/cost estimates for investment in stormwater management is important for the objectives of this research. It shows that stormwater quality/quantity improvements may have a very attractive benefit/cost ratio. The City of Los Angeles and the surrounding region would benefit from new investment in stormwater control with fewer beach closures, cleaner communities, healthier ecosystems, lowered health risks, improved recreational opportunities, and lower demand for potable water. In recent years, California has endured drought. Stormwater has become a source of water recharge for improved surface water/groundwater resources utilization. Other potential benefits of investments on stormwater management in the City of Los Angeles cited in the Currier et al. (2005) study are: aesthetic value of a clean ocean after removal of all ocean impairments; improved ecosystem services in near-shore marine ecological services associated with impairments that would be avoided if urban runoff quality control improvements are implemented; additional water supply (value of water) that could be infiltrated; flood control damages would be lowered, and insurance premiums would decline; property value increases from investments in stormwater management.

A decision support system for reducing pollutant loads and cost of best management practices (BMPs) for stormwater management (BMPDSS) in the Sun Valley watershed (California) was reported by Tetra Tech (2007). The DSSBMP relied on the load simulation program (in C++), or LSPC, by Shen et al. (2004) for predicting pollutants' loads at selected locations of the watershed (see also, Ackerman et al., 2005). Other optimization schemes for selecting stormwater control technologies have been reported by Zhen and Yu (2004) and Lee et al. (2005), among others. Other pollution loading analysis using Geographic Information Systems (GIS) maps have been reviewed (Hauber and Joeres, 1996; Sample et al., 2001; Johnson, 2005; Yorko et al., 2010; Oraei-Zare et al., 2012) and the maps are then used to prioritize areas of investment in SCMs (Heaney et al, 1999). The proposed research borrows from and synthesizes much of the cited work on BMPs, LIDs, and TMDLs and models estimates on stormwater quality (Hoos, 1996; USEPA, 2007, 2008; Water Environment Research Foundation, 2012). In addition, past research has studied a major effect in stormwater called "First Flush" (Larsen et al. 1998; Ma, 2002; Stenstrom and Kayhanian, 2005). The removal of the First Flush will have great results on meeting TMDLs by using simple LID/BMP technologies (Davis, 2005) to remove pollutants (treating small portion of runoff to achieve greater results). For example, the LA RECARGA model simulates bioretention facility performance using either continuous (1-hour time step) rainfall data, or using event-based design storms (City of Los Angeles 2009D). It is known that the largest mass of sediment and contaminant transport is not associated with events of long return intervals (say, over 10 year return inverals), but, rather with events that recur relatively frequently (Rosgen, 2006). From this analysis of storm duration and intensity, it will determine a range of design storms to select SCMs, where the range will cover those events that generate large first pulses of runoff with high concentrations of pollutants. It is estimated that the total cost for implementation of the City of Los Angeles WQCMPUR (Water Quality Compliance Master Plan for Urban Runoff) over the next 20 to 30 years will be in the range of $7 billion to $9 billion (City of Los Angeles 2009B). The financial plan for the WQCMPUR has identified a gap between these estimated costs and the current revenues for the City's Watershed Protection Program. The WQCMPUR recommends that the most sustainable approach for funding future water quality compliance activities is to seek an increase in tax revenues to pay for annual operation and maintenance (O&M) costs and fund Capital Improvement Programs (CIPs) with debt financing.

Figure 1.1 shows several SCMs used in stormwater treatment and control. This research focuses on SCMs that have the capacity to retain stormwater on site, such as dry wells, vegetated swales, infiltration trenches, to conduct local-scale performance of these types of SCMs under controlled conditions. The broad nature of this research and its novelty constitute a solid step forward in the study of the relation between SCMs and water-quality and quantity protection in urban areas. SCMs are increasingly designed to reduce pollutant concentrations at the source, to reduce the volume of runoff that carries pollutants to receiving waters or to remove pollutants from runoff in the storm drain system (Urbonas, 1995; USEPA, 2010; Strecker et al., 2012; Tillinghast et al., 2012). SCMs may be either non-structural (control of pollutants through programmatic activities such as product substitution, education or ordinance implementation) or structural (facilities that improve water quality through some treatment mechanism). The selection of SCMs will be based on minimum design storm criteria and SCM performance criteria. Structural SCMs are also anticipated to result in significant urban runoff reuse and groundwater recharge (Shaver et al., 2007).

The innovative optimization method proposed in this thesis for SCM sizing, placement, and stormwater management captures hydrologic-environmental concerns about the quantity and quality of urban runoff, and lays out a new paradigm for future urban runoff management and a financial plan to support this strategy. The primary goal of the new optimization method is to help meet water quantity and quality regulations at the lowest cost available and using best technologies currently available. Implementation of the proposed new optimization methods in the future will result in cleaner neighborhoods, rivers, lakes, bays, augmented local water supply, reduced flood risk, more open space, and beaches that are safe for recreational uses.

The proposed method for SCM sizing, placement and stormwater management promotes community engagement (public education) with a focus on preventing urban runoff pollution. It will enhance outreach activities to target audiences, establish methods to quantify water quantity and quality benefits; and promote community engagement in urban runoff management activities. The research first objective is to provide a theoretical framework for the optimal siting, selection, and sizing of SCMs for urban stormwater quality management. The second objective of this research is to provide examples of urban stormwater-quality management in a cost effective means through optimal SCM placement. This research work links stormwater quality and quantity characteristics with SCM selection and sizing within an optimization approach that considers the following: (1) SCM design characteristics, (2) water retention and water throughput capabilities of SCMs, (3) SCM water-purification capacity, (4) the cost of SCM implementation, operation and maintenance, (5) the hydrologic and soil characteristics of the areas covered by a network of SCMs, and (6) principles of Low Impact Development (LID) applied to stormwater management by focusing on water-retaining SCMS. The connection of subjects (1) and (6) to obtain globally optimal SCMs represents the originality and impact of this work to the area of stormwater management in urban regions.

		
Grassy Swales / Vegetated Swales (Riverdale Ave Green Street, LA Sanitation Project – City of Los Angeles)	Curb Cuts (Flow-Through Planter Box on Hope St. and 11th St., Private Development Project in Downtown Los Angeles)	Porous Pavement (Los Angeles Zoo Parking Lot, LA Sanitation Project – City of Los Angeles)
		
Rain Cisterns / Rain Barrels (LA Sanitation Project – City of Los Angeles)	Infiltration Trench (Elmer Ave Green Street, LA Sanitation Project – City of Los Angeles)	Dry Wells (Glenoaks/Sunland Stormwater Infiltration, LA Sanitation Project – City of Los Angeles)

Figure 1.1. Selected Stormwater control measures (SCMs) used in stormwater treatment.

2. OPTIMIZATION PROGRAMING - RESEARCH DESCRIPTION

2.1 Case Study

The case study area is located within the City of Los Angeles (the City). The study area (watershed) drains to a common low point and water moves through underground and surface drainage pathways that converge into streams and rivers. Eventually the water reaches a receiving waterbody such as a river, stream, lake, wetland or the ocean. The surface water flow after rainfall events is characterized as stormwater or urban runoff:

- **Stormwater** is the water from rain events and that flows over the City's streets, storm drain system, streams and rivers, beaches, wetlands, estuaries, bays and harbors. In the study area in southern California (City of Los Angeles) stormwater occurs almost exclusively during the wet weather season from November 1st to March 31st. The dry weather season exists from April 1st to October 31st.
- **Urban runoff** includes stormwater, but also other sources of water not directly associated with rain events. Urban runoff includes natural sources such as groundwater seepage and springs. It includes anthropogenic sources of water, such as landscape overwatering, car-washing, illegal connections to the stormwater system, illegal dumping and treated water from industrial facilities (each requiring a specific permit). Urban runoff occurs in some form throughout the year, though the magnitude of flow tends to be much greater after rain events. Urban runoff is collected by the City's storm drain system. This is a system of underground pipes, devices, conveyance networks and treatments that is completely separate from City of Los

Angeles' sewer system, which collects residential, commercial and industrial wastewater. Except for unlawful connections, there is no sewage entering into the storm drain system. The storm drain system typically starts on City streets with the drainages that convey runoff to the storm drain inlets named as "catch basins". Almost all catch basins are marked with "do not dump – drains to ocean" warnings signs. The catch basins may have external screens and/or internal capture devices to separate trash from urban runoff. The catch basins provide a visible "connection" between the City of Los Angeles watersheds and an underground pipe network of small pipes connecting to larger pipes, ultimately empting into constructed channels or streams and creeks. The smaller creeks and streams may empty into wetlands, lakes or flood control basins. The larger water flows generally end up in rivers that release water into harbors or directly into the ocean.

Watersheds can be fragment down into smaller sub-watersheds, basins and catchments, divisions that depend on site-specific conditions, inter-jurisdictional attentions or on the level of detail needed for effective management. A portion of a watershed may have distinctive environmental factors, be subjected to certain historical deficiencies or fall under the political jurisdiction of multiple agencies.

2.2 Watershed Area of Case Study

It will become apparent that there are complex interrelationships within a watershed that require a great deal of cooperation among responsible agencies when discussing watershed management. This chapter introduces some of these important watershed quality management issues. The City of Los Angeles lies within four major watersheds (City boundaries has an area of 473 squared miles (1,225 km^2)). The boundaries are illustrated in Figure 2.1 and the total watershed areas and portions within the City are summarized in for the following watersheds***:***

- **Los Angeles River watershed** – This is the largest regional watershed shown on Figure 2.1 and significant portions of impaired sub-watersheds are within City boundaries. For water quality compliance with respect to metals, the watershed has been divided into six "jurisdictional groups." The City has joint responsibility for water quality management in each of these defined areas. Water from the Los Angeles River discharges into San Pedro Bay from the Los Angeles River Estuary. The Los Angeles River watershed is the largest of the four area watersheds and includes all the lands draining into the Los Angeles River, Figure 2.1. The river is 51 miles long (1 mile = 1,609.3 meter), initiates in the western San Fernando Valley in Canoga Park and discharges into San Pedro Bay. The first 30 miles of the River are within the City of Los Angeles. The total watershed area is 833 square miles, with about 324 square miles of the upstream portion covered by the forest and open space of the Santa Monica, Santa Susana and San Gabriel Mountains. Los Angeles River tributaries originate at an elevation of 795 feet (1 foot = 0.3048 meters) in the western part of the San Fernando Valley gathering runoff from the northern slopes of the Santa Monica Mountains (North of Mulholland Drive) and the southern slopes of the San Gabriel Mountains. The steep slope of the River, averaging about 16 feet per mile, results in speedy drainage to the San Pedro Bay at Long Beach.

- **Santa Monica Bay watershed** – The Santa Monica Bay watershed is comprised of numerous sub-watersheds emptying into Santa Monica Bay. The northern portions of the watershed, outside the Los Angeles City limits, extend to the Los Angeles County/Ventura County Line, Figure 2.1. To the south, the watershed extends to the Palos Verdes Peninsula. There is also the very small Marina del Rey sub-watershed that can be viewed as part of the Santa Monica Bay watershed, but it is sometimes treated as a separate watershed with respect to water quality management. The Santa Monica Bay watershed runs along the coast from the Ventura-Los Angeles County line in the north to the Palos Verdes Peninsula in the south, and has a total watershed area of 285 square miles (not including the Ballona Creek watershed, which also discharges into Santa Monica Bay). As mentioned previously, the Marina del Rey watershed could be viewed as a sub-watershed of the surrounding Santa Monica Bay watershed. The total area of the Marina del Rey watershed is 2.9 square miles – a small percentage of the Santa Monica Bay watershed.
- **Ballona Creek watershed** – This watershed contains the Ballona Creek, Ballona Creek Estuary and Ballona Creek Wetlands, Figure 2.1. As the Ballona Creek discharges into the Pacific Ocean, the Ballona Creek watershed could also be viewed as a sub-watershed of the Santa Monica Bay watershed. The Ballona Creek watershed is located on the coastal plain of the Los Angeles basin, with the Santa Monica Mountains to the north and the Baldwin Hills to the south. This watershed collects runoff from the southern part of the Santa Monica Mountains (south of Mulholland Drive) and the western part of the City of Los Angeles and

drains into Santa Monica Bay. Ballona Creek is predominantly channelized and the watershed is highly developed with both residential and commercial properties. The Ballona Creek has a drainage area of approximately 128 square miles.

- **Dominguez Channel watershed** – This watershed includes the drainage areas of the Dominguez Channel, the Wilmington Drain/Machado Lake, Dominguez Channel Estuary and the Torrance-Carson Channel that all eventually discharge through the Dominquez Channel into the Los Angeles Harbor area, Figure 2.1. The Los Angeles/Long Beach Harbor is itself subdivided into several distinct waterbodies. The Dominguez Channel watershed is also termed a "management area" that includes some land with storm drains that do not empty into Dominguez Channel, but is geographically connected with the land that does drain into the channel. This area includes the communities of Wilmington and San Pedro. The Dominguez Channel watershed is the most urbanized watershed in Los Angeles County. In the northern and eastern portions of the watershed, the Rosecrans and Dominguez Hills rise to about 200 feet elevation. In the southwest portion of the watershed, the Palos Verdes Hills rise to an elevation of 1,480 feet. The Dominguez Channel drains an area of approximately 109 square miles into the Los Angeles Harbor/Long Beach Harbor areas**.** The forty-acre (1 acre = 4,047 m^2) Machado Lake is located in the Wilmington section of this watershed within the Ken Malloy Harbor Regional Park.

Geographically, the four watersheds are substantially different from each other. Some of the important topographic features of the region are illustrated in Figure 2.1**.**

2.3 Impaired Watersheds and Reaches in the City of Los Angeles

Figure 2.2 shows the 303(d) list-impaired subwatersheds and reaches for the Los Angeles area (California Regional Water Quality Control Board, 2012). The Clean Water Act's section 303(d) requires each state in the United States to identify the waters within its boundaries that do not meet water quality standards. Water bodies that do not meet the water quality standards are considered impaired and are placed on the 303(d) list. Then for each listed water body as shown in Figure 2.2, the State of California is required to establish a TMDL of each pollutant impairing the water quality standards in that water body. A TMDL is a tool for implementing water quality standards and is based on the correlation between pollution sources and streams water quality conditions. The TMDL established the allowable pollutant loadings for the water body and established water quality based controls. Many receiving waters within Los Angeles do not meet water quality criteria and have been classified as impaired on the federal Clean Water Act for the 303(d) list.

2.4 SCMs Costs, Operations, and Maintenance

The following SCMs will be reviewed in the study research plan, for Cost, Operations, and Maintenance: Screens for Catch Basins, Dry (percolation) Wells, Infiltration Trenches, Detention Tanks, Grassy Swales (Planter Boxes). Table 2.1 shows the unit cost for these five SCMs with the added ten (10) years of Operations and Maintenance (O&M) (City of Los Angeles, 2014). It also shows the approximate removal efficiency of pollutant concentration for trash, sediments, oil/grease, and bacteria pollutants. These costs were added to the optimization programing in the following chapters of this research work.

2.5 Soil Types for SCMs

Table 2.2 shows the different infiltration soil types within the City of Los Angeles: Loam, Sandy Loam, Loamy Sand, and Engineered Soil. This information is important to determine which soils can capture stormwater by infiltration and which ones cannot. If an area's soil does not have sufficient infiltration capacity then a planter box or grassy swale with a liner is used instead (flow-through devices).

2.6 SCMs for LID

Figure 2.3 shows the SCMs for the City of Los Angeles Low Impact Development for Residents and Developers (City of Los Angeles, 2009A, 2011). Figure 2.3 also shows the SCMs for the most effective Low Impact Development application. For larger projects, a more detailed SCMs that can be used to meet the permit requirements for the City of Los Angeles (City of Los Angeles, 2009C, 2011).

2.7 Separate Systems for Sewage Collection and Urban Runoff Conveyance

The City of Los Angeles has separate sewage and urban runoff collection systems. Most cities in the west coast of the United States have separate systems, in contrast to east-coast, older, cities that have a combined system which are sewage-stormwater system. A combined sewage-stormwater conveyance system makes treatment of low-flow stormwater relatively easy at sewer treatment plants, but during heavy rains the combined sewage-stormwater flow exceeds treatment capacity and some of that flow must be released untreated to receiving waters. The City of Los Angeles has 1,500 miles of pipes, 100 miles of open channels, and 38,000 catch basins. These storm drains are managed by City of Los Angeles, Los Angeles County, and Army Corp of Engineers. For separate systems, the conveyance flow is not treated and reaches waterbodies in raw condition (mostly stormwater drains into the Pacific Ocean). The estimated storm drains conveys over 50 million gallons per day of dry-weather flow and over 10 billion gallons per day of wet-weather flow in the City of Los Angeles. These numbers show it is infeasible to treat the wet-weather flow. The City of Los Angeles would need hundreds of treatment plants to handle these large flows (City of Los Angeles, 2011). All the different agencies must work together to implement SCMs that can be used to meet stormwater permit requirements and handle large wet-weather flows in the waterways.

Table 2.1. Estimated cost and approximate removal efficiency rates for different SCMs in Los Angeles area.

SCM type	Unit Cost with O& M ($/cubic ft)	Maximum Capacity (Cubic Feet)**	Cost with O&M for Ten-Year Service Life***	Concentration Removal (%)				O& M Annual Cost ($)	Cost per 10 Year Service Life ($)	Rain Fall (cubic feet)*	Rain Fall (gallons)*
				Trash	Sediments	Oil & Grease	Bacteria				
Screen for Catch Basins	$42	60	$2,520	90	30	20	20	$100	$1,000	2,450	18,130
Dry Well	$66	495	$32,670	90	75	70	70	$750	$7,500	2,450	18,130
Infiltration Trench	$30	2,450	$73,500	90	75	70	70	$2,500	$25,000	2,450	18,130
Detention Tank	$30	2,450	$73,500	90	75	70	70	$2,500	$25,000	2,450	18,130
Grassy Swale (Planter Box)	$54	2,160	$116,640	75	75	60	70	$2,700	$27,000	2,450	18,130

1 cubic foot = 0.02832 m^3
O&M: Operation and Maintenance
**Based on one-acre impervious site that captures up to 0.75 inches in 48 hours (1 inch = 2.54 cm)*
***The capacity to store stormwater includes 0.40 porosity whenever applicable*
****Equals the unit cost times the capacity*

Table 2.2 Infiltration soil types.

Soil Type	Infiltration Rate (in/hr)*	Planter Surface Area (ft^2)#	Volume of Runoff (ft^3)	Surface of Impervious Area (ft^2)	Depth of Planter Box Soil (ft)	Maximum Ponding Depth (ft)	Maximum Planter Box soil Infiltration Rate (in/hr)
Loam	0.5	124	140	2,500	3	1	5
Sandy Loam	1.0	112	140	2,500	3	1	5
Loamy Sand	2.4	88	140	2,500	3	1	5
Engineered Soil	5.0	62	140	2,500	3	1	5

**** The calculation is for a single family home that has a 5,000 sq. ft lot and a 2,500 sq. ft impervious area. The 0.75 inch stormwater runoff is approximately 140 cubic feet.***

 # The stormwater runoff is calculated according to the City of Los Angeles' LID Manual 2012 using the planter box surface area needed for a given soil type.

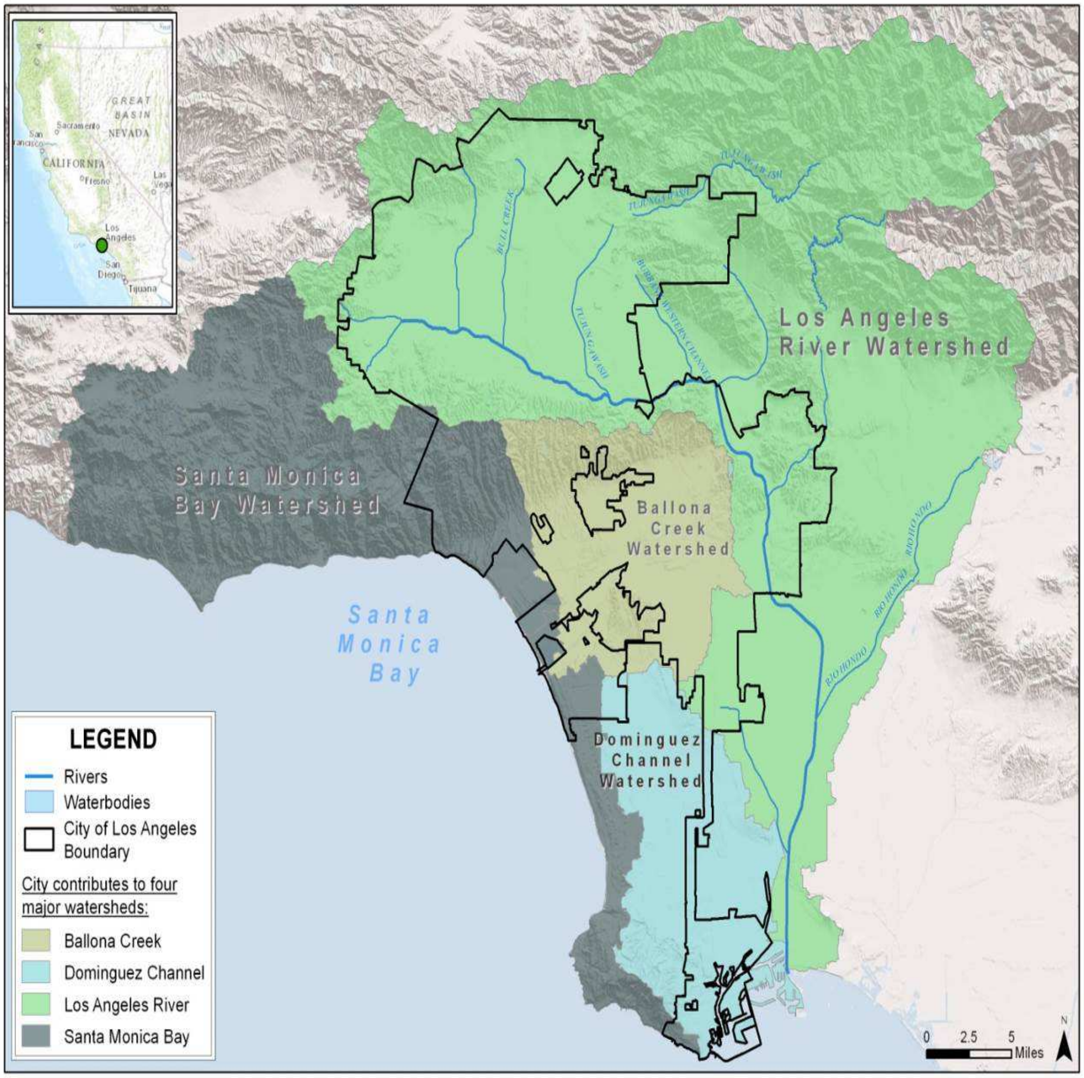

Figure 2.1. Map of City of Los Angeles (perimeter in black line) showing the four watersheds in the City of Los Angles boundary.

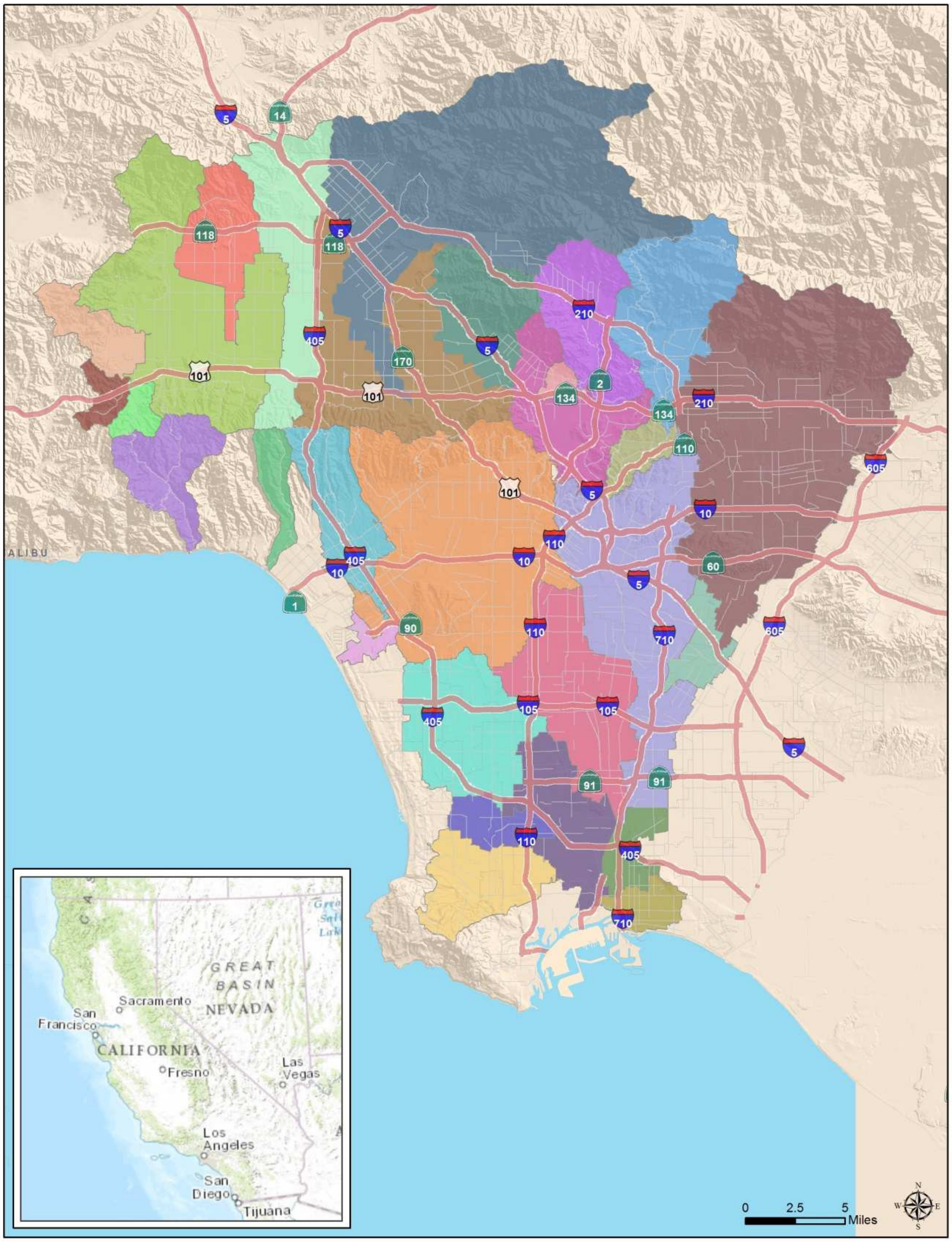

Figure 2.2. Map of Los Angeles showing the 303(d) list of impaired sub-watersheds and reaches for the Los Angeles area.

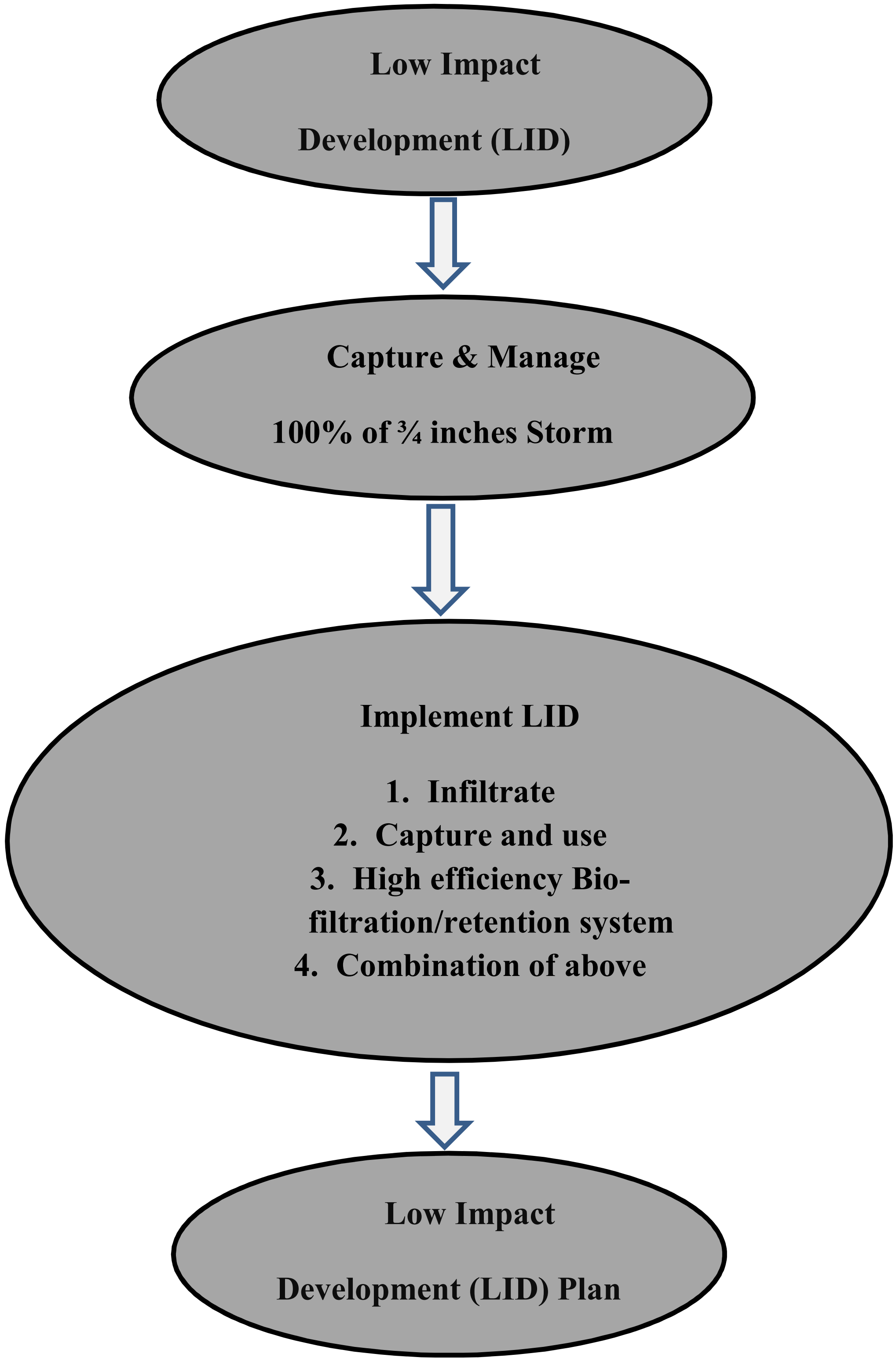

Figure 2.3. The Los Angeles Low Impact Development for Residents and Developers showing different SCMs.

3. RESOURCES AVAILABLE FOR RESEARCH OPTIMIZATION PROGRAMMING

3.1 SCM Selection (Mathematical Programming for SCM Selection and Sizing)

3.1.1 The Study Area, Water-retaining SCMs, and Study Objectives

The study area used in this chapter lies within the boundaries of the City of Los Angeles, California. Figure 3.1 shows a map for the City boundaries, which has an area of 473 squared miles (1,225 km^2), and 17,400 miles of streets (28,000 km), with a population of about 4 million people. Los Angeles' storm drain system consists of 1,500 miles of pipes (2,414 km), 100 miles of open channel (161 km). There are four major watersheds in the City of Los Angeles (Ballona Creek, Dominguez Channel, Los Angeles River, Santa Monica Bay) shown in Figure 3.1. The stormwater control system in Los Angeles includes about 38,000 catch basins and thousands of other SCMs. Its average daily dry weather and wet-weather runoffs are about 50 million gallons (189,250 m^3) and 10 billion gallons (37,850,000 m^3), respectively [LA Sanitation, City of Los Angeles, 2013].

The City of Los Angeles has implemented many of the known types of SCMs (LID, Green Infrastructure, etc.) and must meet a variety of statutory TMDLs imposed on urban stormwater (Schueler, 1987; Hoos, 1996; City of Los Angeles, 2011; Damodaram and Zechman, 2013). A peculiar phenomenon observed in the study area, that adversely impacts stormwater quality, is the "first flush" stormwater contamination (Larsen et at., 1998; Ma, 2002). This is the generation of large amounts of stormwater pollutants during the first few storms over urban areas following a dry pollutant-accumulation period during the summer season. This first flush phenomenon is well established by historical stormwater-quality data from cities featuring a Mediterranean-like climate with dry summers and relatively wet winters found in the American west coast (City of Los Angeles 2009D; 2009E; Rosgen, 2006). Thus, an effective effort to diminish the pollution of receiving water bodies by heavily contaminated stormwater in such climatic regions must address first-flush impacts (Stenstrom and Kayhanian, 2005). One way to accomplish this is by deploying LID/SCMs that retain stormwater and its pollutants at the point of origin or through their pathways through urban areas (Davis, 2005). One effort to counter the first-flush pollutant loading was the development and implementation of the LA Recarga model by the City of Los Angeles (City of Los Angeles, 2009D). The latter model simulates water and pollutant retention at SCMs by infiltration and deep percolation of stormwater at locations with suitable soil permeability and groundwater characteristics.

The principle of retaining stormwater pollutants at or near their point of origin is a theme pursued in this research. It seeks to illustrate the following themes to readers: (1) the use of green streets SCMs for stormwater pollutant retention; (2) promote the benefits of using green streets to manage stormwater to improve the beneficial uses of receiving water bodies, reduce potential risks for human safety and health, preserve aquatic plant habitats, improve water quality, support water conservation, and recharge groundwater supplies. Figure 1.1 (in Chapter 1) displays several SCMs that capture rainfall (cisterns) and retain (wholly or partly) stormwater at their points of origin. Green streets SCMs included permeable pavers, porous pavement, vegetated curb cuts, curb bump outs, and vegetated swales bordering streets. Infiltration trenches under streets, and percolation wells that capture stormwater moving through streets are part of the suite of green street SCMs. Permeable rain gardens and green roof diminish storm runoff by increasing the infiltration of the substrate on which rain falls.

There are other types of SCMs that are used in conjunction with the water-retaining and filtration-type SCMs depicted in Figure 1.1. Those include detention ponds, sedimentation basins, and catch basins. There are also preventive-type SCMs, such as street sweeping, that remove pollutants from streets prior to storm events. Non-structural SCMs included public education campaigns against littering, the excising of penalties for dumping of polluting materials and trash, the placement of recycling bins and trash cans at locations with heavy public frequentation, and the offering of access by the public to recycling centers for disposal of toxic wastes or hazardous materials.

This chapter presents a modeling approach to SCM selection and case study of SCM deployment within the City of Los Angeles, California. This study relies on a data set that includes records of rainfall, land use, soils, groundwater, streets and storm-conveyance infrastructure, non-point and point sources of pollution to storm runoff, and green SCMs. The study's first objective is to provide a theoretical framework for the optimal siting, selection, and sizing of SCMs for urban stormwater quality management. The second objective of this study is to provide examples of urban stormwater-quality management in a cost effective manner through optimal SCM deployment (Loaiciga et al., 2014; Sadeghi et al., 2015). The SCM examples presented in this research work are intended to:

(1) Provide a better understanding of SCM designs for green street and alley elements;

(2) Support the benefits of using green infrastructure to manage stormwater and improve;

(i) The quality of receiving water bodies;

(ii) Reduce potential risks for human safety and health;

(iii) Preserve aquatic habitats;

(iv) Promote water conservation and recharge to groundwater.

Stormwater quality protection is a perennial, resource-intensive task, involving institutional intervention and the input of capital, management, and labor to install, maintain, and replace SCMs. The research has schematized in Figure 3.2 the phases and institutional steps needed in achieving effective stormwater quality management using SCMs. This research is concerned with vulnerability assessment, optimization, and field investigations of stormwater quality using SCMs, as described in the following sections.

3.2 Methodology

3.2.1 Geographical/Environmental Analysis for Determining the Spatial Vulnerability to Stormwater Pollution

The optimal allocation of SCMs in a large urban area such as the City of Los Angeles (1,225 km^2, population about 4 million people) requires the analysis of multiple phenomena. Among these are watershed variables (rainfall, soils, topography, groundwater levels), land use, pollutants' sources and loading, and infrastructure (streets, storm drains) distribution. The stormwater analyst gains insightful information by determining the geographical distribution of stormwater pollutants loadings vulnerability index within an urban area. This produces the density of specific stormwater pollutants of interest (or indicator pollutants) expressed as a mass or volume of pollutant per unit surface area per unit time, or as a mass of pollutant per volume of runoff generated per unit time within an urban district. Trash accumulation within an urban district, for example, is expressed in cubic meters of trash per hectare per day (or in cubic yards of trash per acre per day). Hydrologic/environmental analysis within an urban area leads to the estimation of the runoff produced by rainfall design events or storm events and its associated concentration of indicator pollutants in stormwater (say, dissolved total nitrogen in mg/L, or most probable number (MPN) of indicator microorganism per liter of stormwater). High demographic density and high density of roads per unit of land are commonly associated with high pollutant loading (City of Los Angeles, 2002).

The ascertaining of pathways followed by pollutants carried in stormwater as it moves overland or through conveyance infrastructure through an urban area is essential to determining where to deploy SCMs. The size and type of SCM best suited for a specific location are determined by (i) the amount of runoff converging on the point of interest, (ii) the type of targeted pollutant and its concentration, (iii) site accessibility and physical conditions that may allow or disallow a type of SCM, (iv) cost of installation and maintenance of SCMs, and (iv) local ordinances that that may or may not permit certain types of SCMs to be deployed at a site. As an example, trash laden stormwater may be tackled by screened basins, but not by percolation wells. Or, microbially contaminated stormwater may call for the deployment of percolation wells that inject stormwater into permeable subsurface formations to be followed by biological decay underground. Critical to the selection of a percolation well or any other type of infiltrating SCM is the existence of a permeable substrate and a phreatic surface below the zone of stormwater injection.

Pollutant loading, stormwater generation by rainfall, runoff movement through an urban watershed, and land characteristics (topography, infiltration capacity of soils, groundwater depth) are all spatially distributed variables. They can be combined and displayed in map form as an index of vulnerability to stormwater quality degradation. To construct such vulnerability index, this work proposes the production of digital thematic maps for a stormwater management study area of (i) soils, (ii) topography, (iii) land use (including types such as residential, commercial, industrial, parks, mixed use), (iv) rainfall depth for events of selected frequency and duration, (v) depth to groundwater, and (vi) pollution loads. The mapped thematic spatial variables are interpreted as geo-referenced random variables. Specifically, let soil infiltration capacity (= K*(x,y)), rainfall depth (P*(x,y)), land use and corresponding percentage impervious area A*(x,y), slope (S(x,y)), pollutant load L*(x,y) during an accumulation period, and depth to groundwater, D*(x,y), be random variable spatially indexed by coordinates x and y in a common geographic reference system. Each of the former random variables isnormalized by a maximum value to obtain normalized (between 0 and 1) random variables, which we denote by the symbols A, D, K, L, P, and S, respectively. Probability density functions (pdfs) are then derived for Y = 1/K, A, S, L, P, and Z = 1/D using values of the chosen variables available from various sources. The stormwater quality vulnerability V(x,y) equals the vulnerability index. It is defined as follows:

$$V(x,y) = A(x,y) \cdot L(x,y) \cdot S(x,y) \cdot P(x,y) \cdot Y(x,y) \cdot Z(x,y) \tag{3.1}$$

In equation (3.1), the increase in any of the involved random variables on its right-hand side increases the vulnerability to stormwater quality degradation, and vice versa. Knowing the pdfs of the variables on the right-hand side of equation (3.1) allows the derivation of the pdf of the vulnerability index V using statistical theory. Geographic space is then classifiable according to the probability equation 3.2:

$$P[V(x,y) \leq v] = p \quad (3.2)$$

Candidate non-overlapping categories for vulnerability index mapping could be $0 \leq p < 0.25$, $0.25 \leq p < 0.50$, $0.50 \leq p < 0.75$, $0.75 \leq p < 1.0$, each of these categories corresponding to a vulnerability index being low, medium, high, and very high, respectively. A color code scheme is assigned to the probability categories to prepare a color-coded vulnerability index map, as portrayed in Figure 3.3. This map would prioritize the areas where SCM deployment is most needed. Specifically, areas with high and very high vulnerability indices are those requiring greater investment in stormwater management. A study by City of Los Angeles LA Sanitation and Cal Poly University Pomona called Greenways to Rivers Arterial Stormwater Systems (GRASS) has shown that effective impervious area is more important than percent impervious area (City of Los Angeles, 2013). This shows that SCMs deployment and management is very important in meeting the pollutant load reduction in cities across USA.

Figure 3.4 shows a soil classification map compiled by the US Geological Survey (USGS) for the Los Angeles area. The soils map also shows the saturated hydraulic conductivity in in/hr for each soil type. Other spatially referenced data for Los Angeles area, such was land use category representation (Figure 3.5), potential landside (Figure 3.6), pervious and impervious area (Figure 3.7), topography, depth to the phreatic surface/groundwater (Figure 3.8), liquefaction zones (Figure 3.9), flood-prone areas (Figure 3.10), miscellaneous pollutant loadings, streets and storm drain infrastructure (stormwater flood control priorities Capital Improvement Projects (CIP)) (Figure 3.11), are available from the LA Sanitation - City of Los Angeles (2013 data).

3.2.2 Creation of Storm Runoff and Pollution Loading SCM-Applicability Maps

Digital thematic maps for the study area of (i) soils, (ii) topography, (iii) land use (residential, commercial, parks, etc.), (iv) rainfall, (v) depth to groundwater level, (vi) pollution sources, (vii) receiving water bodies, in geographical information system (GIS) format were analyzed to prioritize areas according to their need for stormwater management and SCM implementation. Figure 3.12 shows a map of trash production rates within the boundaries of the City of Los Angeles showing that high trash accumulation rates occur in areas surrounding major highways and densely populated areas. Figure 3.13 depicts the boundaries of catchments with water quality prioritization index for the Los Angeles regional watersheds. Figure 3.14 shows the boundaries of the Los Angeles regional 50 year – 24 hour rain amounts in inches.

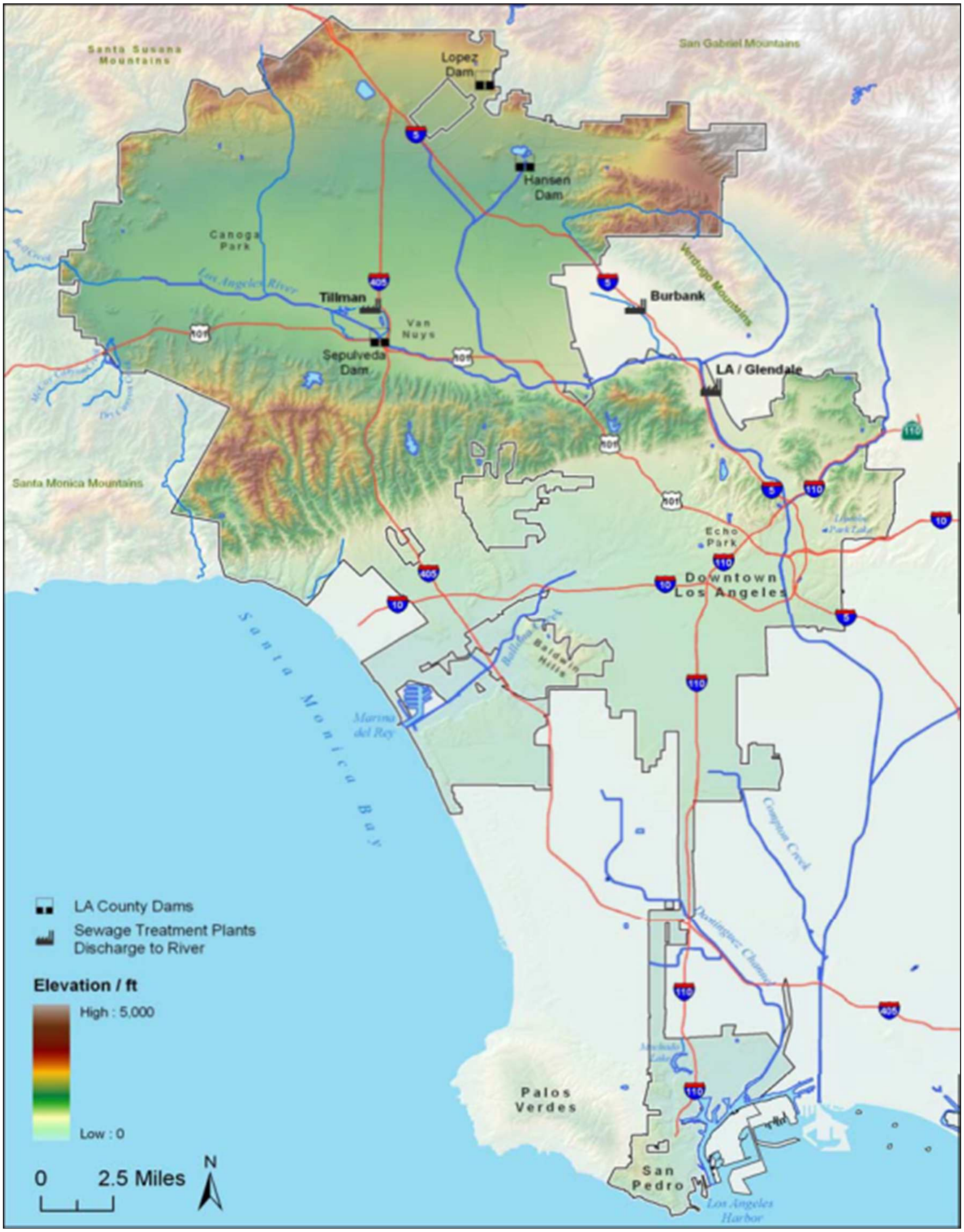

Figure 3.1. Boundaries of the City of Los Angeles (Topographic and Significant Hydraulic Features within City of Los Angeles).

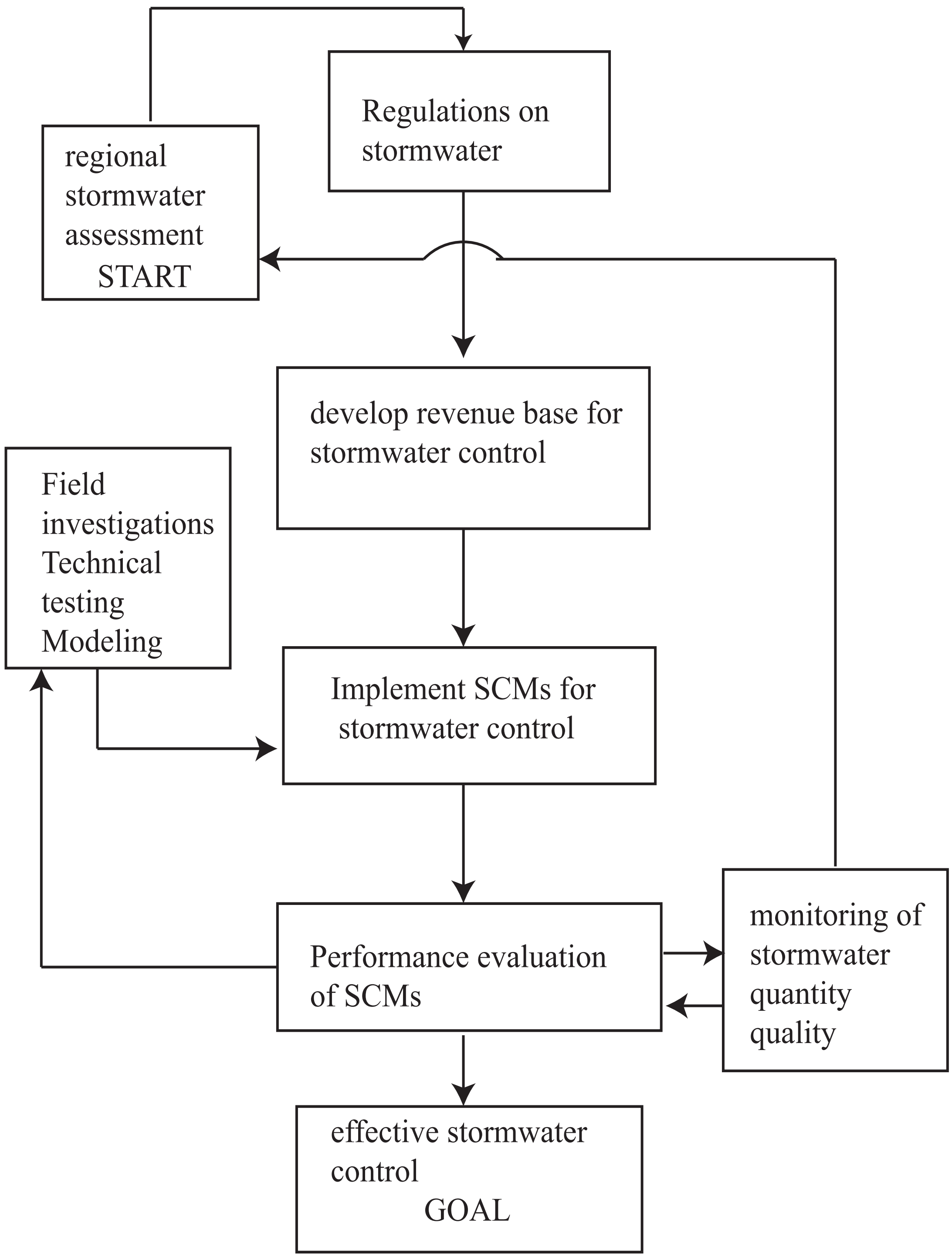

Figure 3.2. Key tasks for successful implementation of SCMs (technical and institutional requirements and their interactions leading to improved storm water quality).

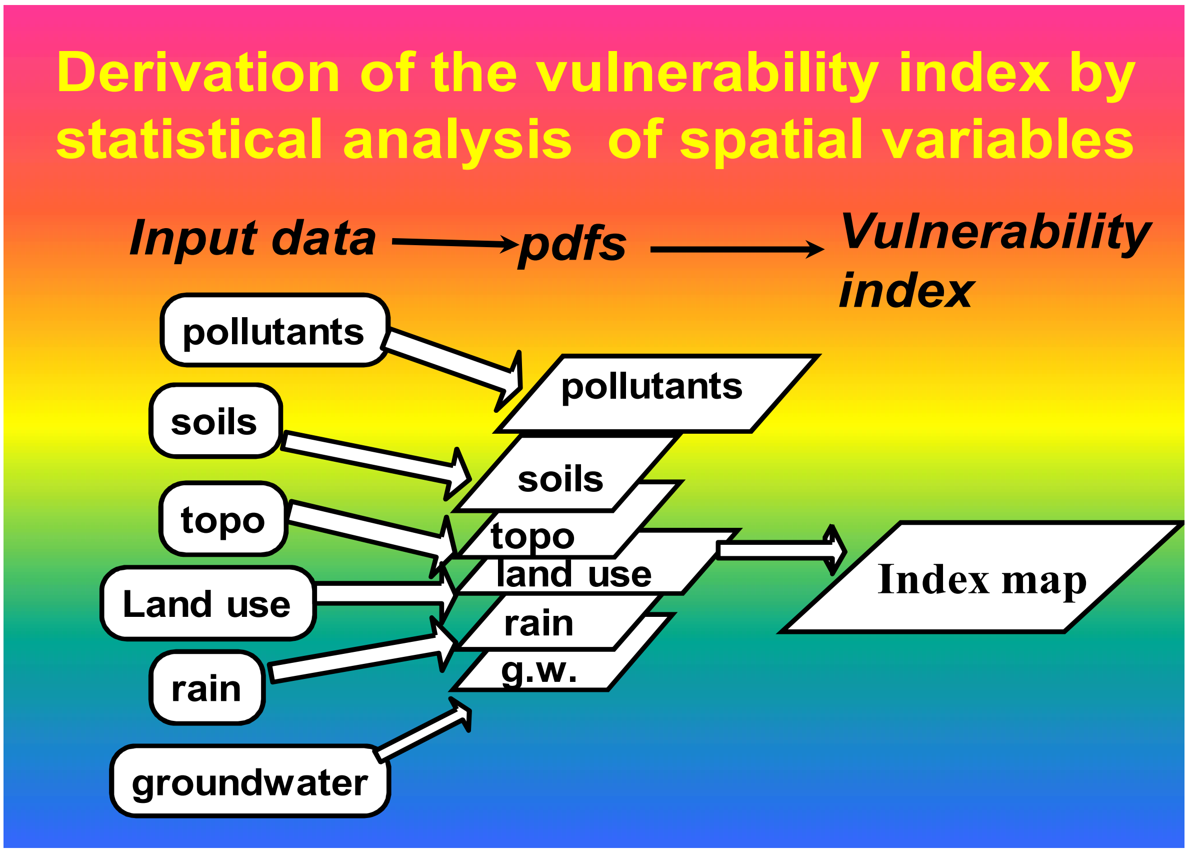

Figure 3.3. Processing of spatial random variables leading to a probabilistic index map of the vulnerability to stormwater quality degradation (pdfs: probability density functions; g.w.: groundwater).

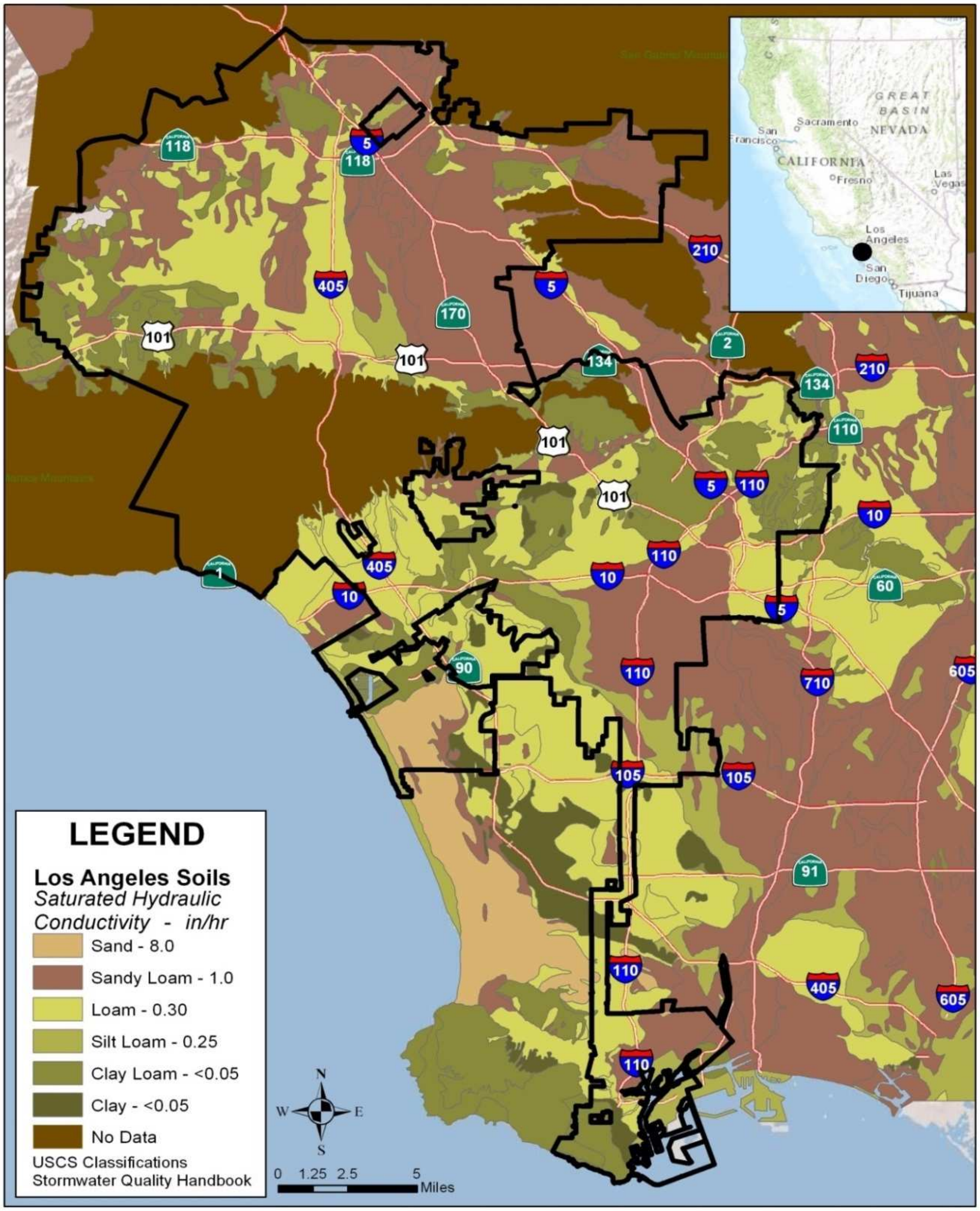

Figure 3.4. Soil classification map and values of saturated hydraulic conductivity for each soil type (US Geological Survey (USGS) Classifications Stormwater Quality Handbook).

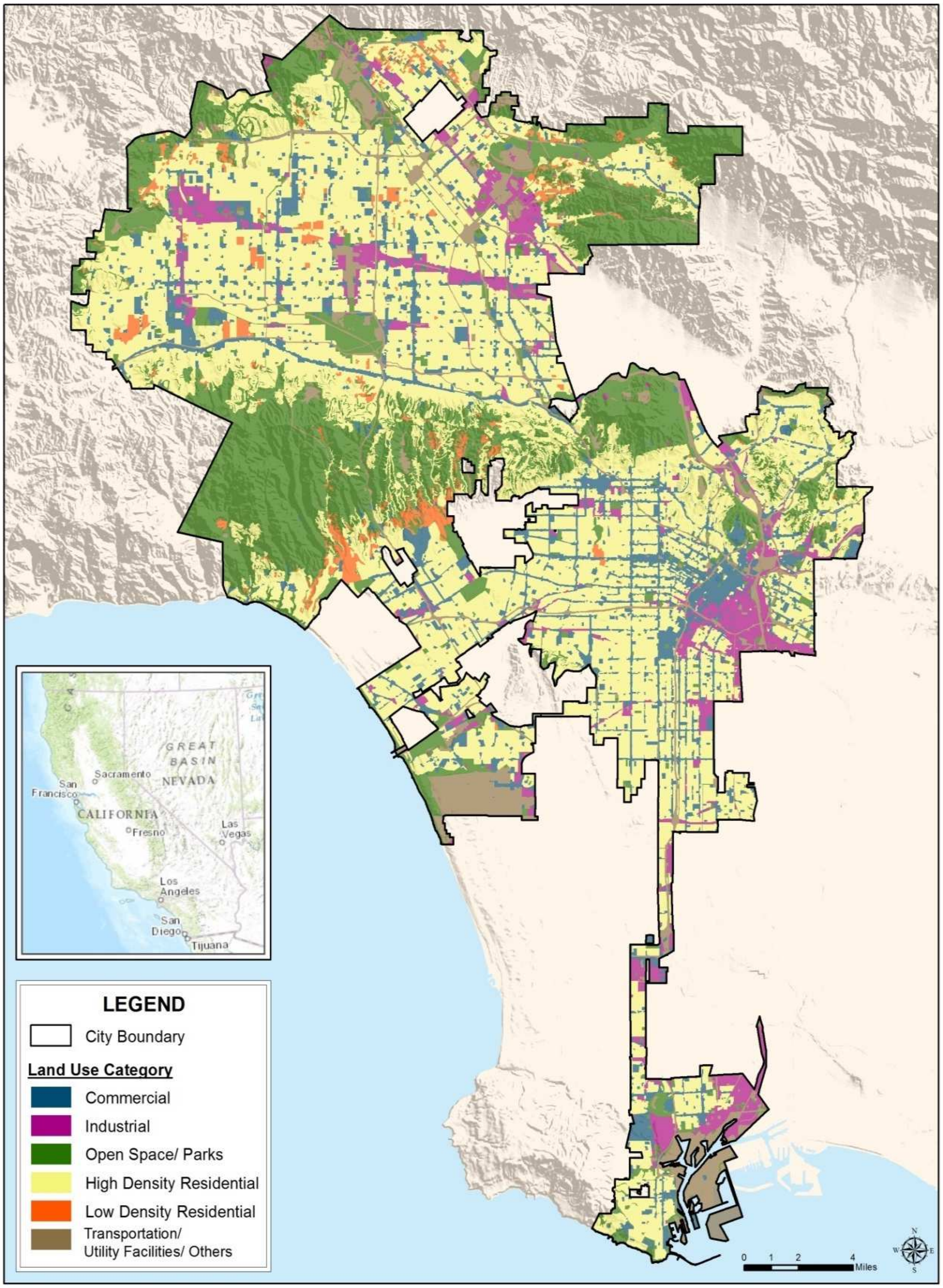

Figure 3.5. Land Use Category representation in Los Angeles regional Watersheds (Southern California Association of Governments (SCAG) 2005).

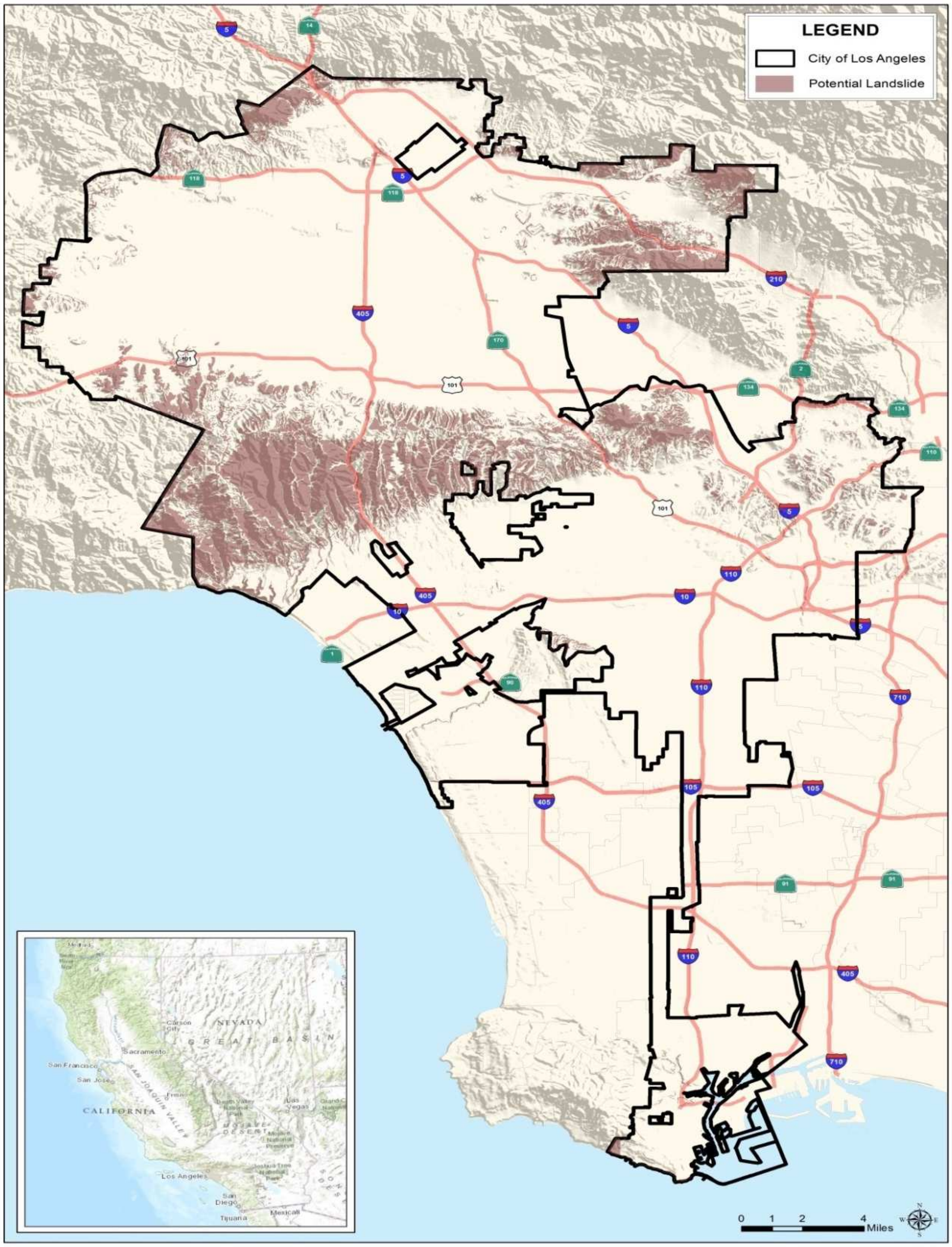

Figure 3.6. Potential landside for the Los Angeles regional watersheds (Bureau of Engineering, Geotechnical Division, City of Los Angeles).

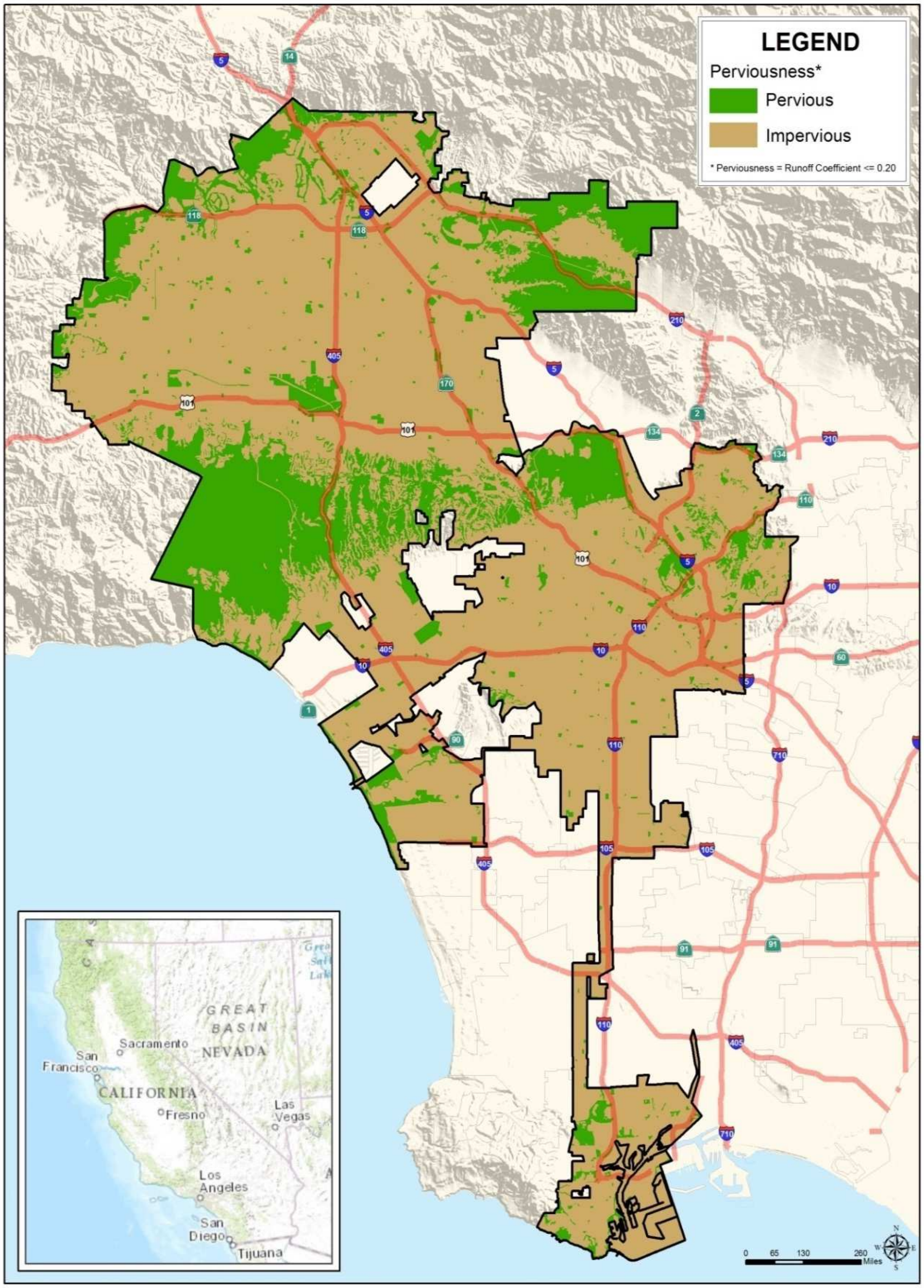

Figure 3.7. Pervious and impervious area for the Los Angeles regional watersheds (Southern California Association of Governments (SCAG) 2005).

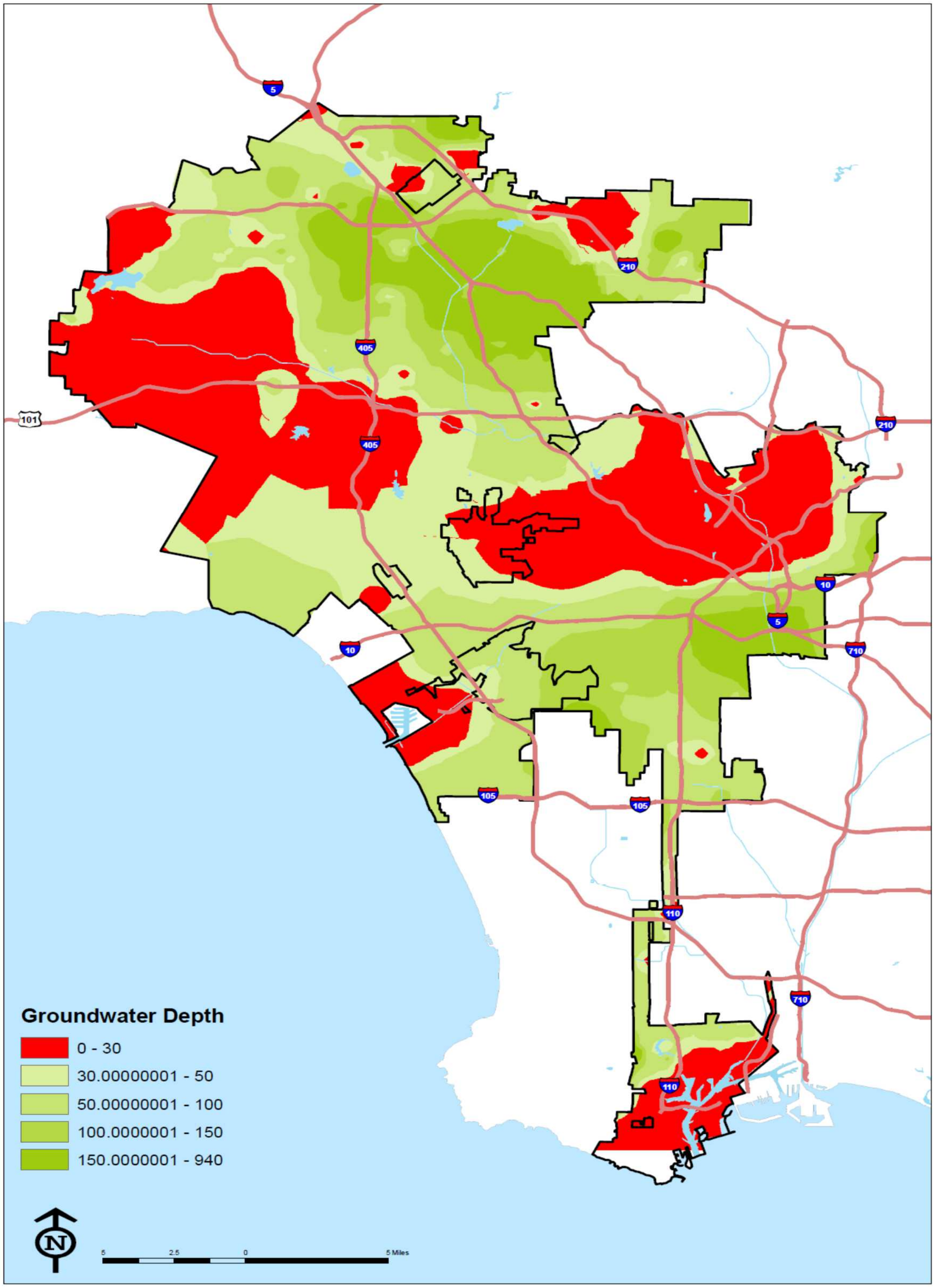

Figure 3.8. Groundwater depth for the Los Angeles regional watersheds (Water Master, Los Angeles County).

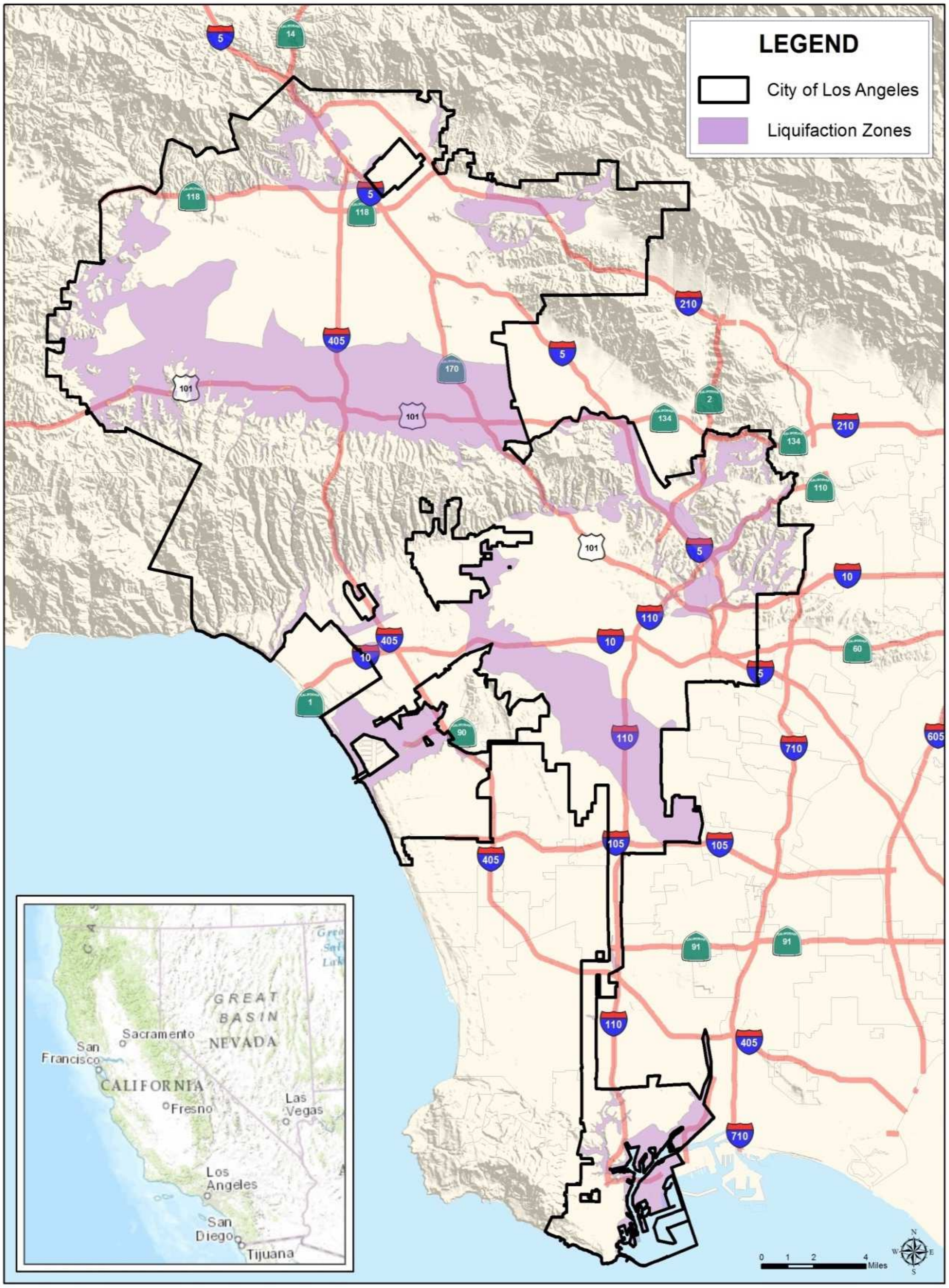

Figure 3.9. Liquefaction zone for the Los Angeles regional area (Bureau of Engineering, Geotechnical Division, City of Los Angeles).

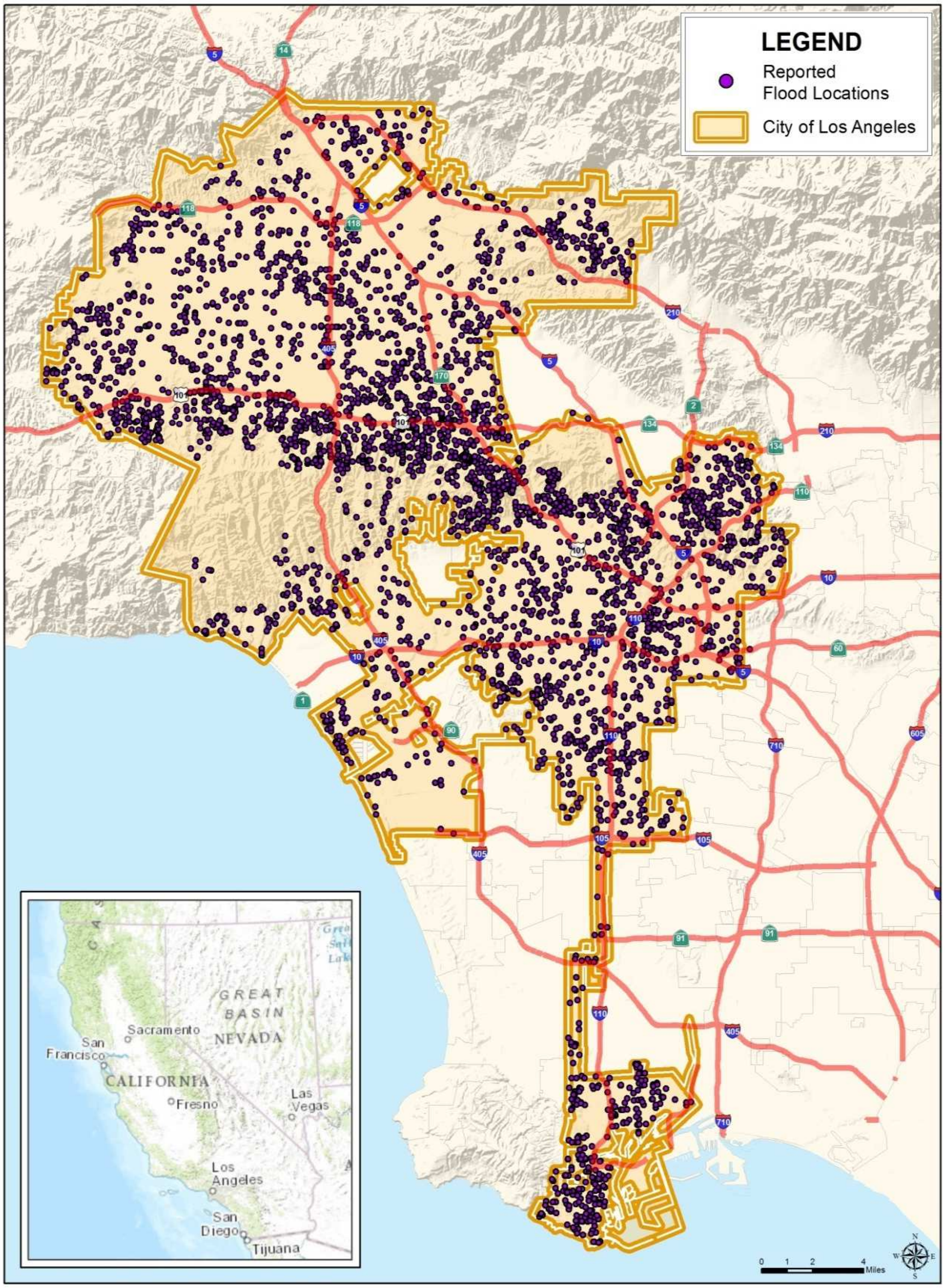

Figure 3.10. Report of flooded areas for the Los Angeles regional watersheds (Bureau of Engineering, City of Los Angeles).

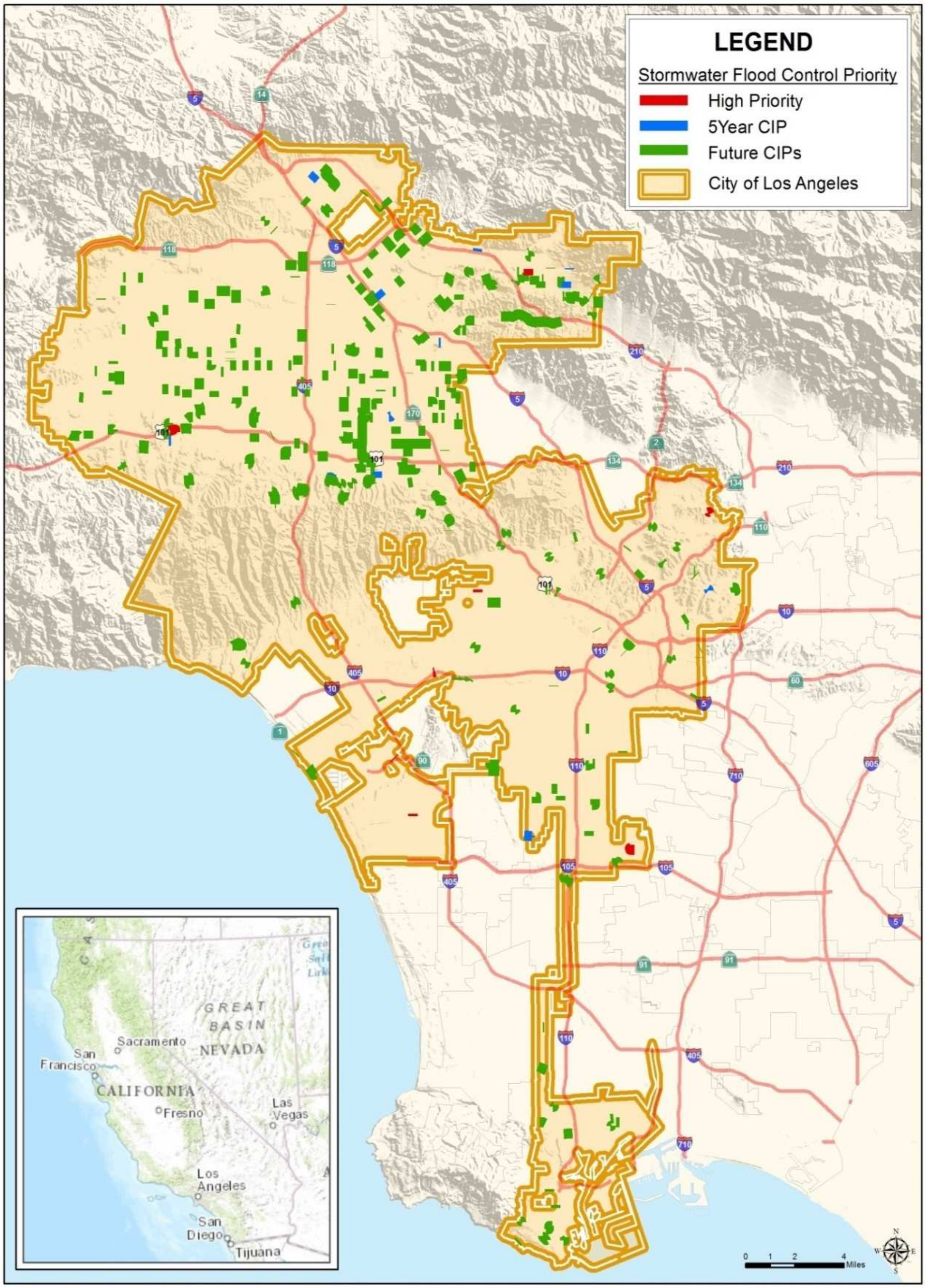

Figure 3.11. Stormwater flood control priorities Capital Improvement Projects (CIP) for the Los Angeles regional watersheds (Bureau of Engineering, City of Los Angeles).

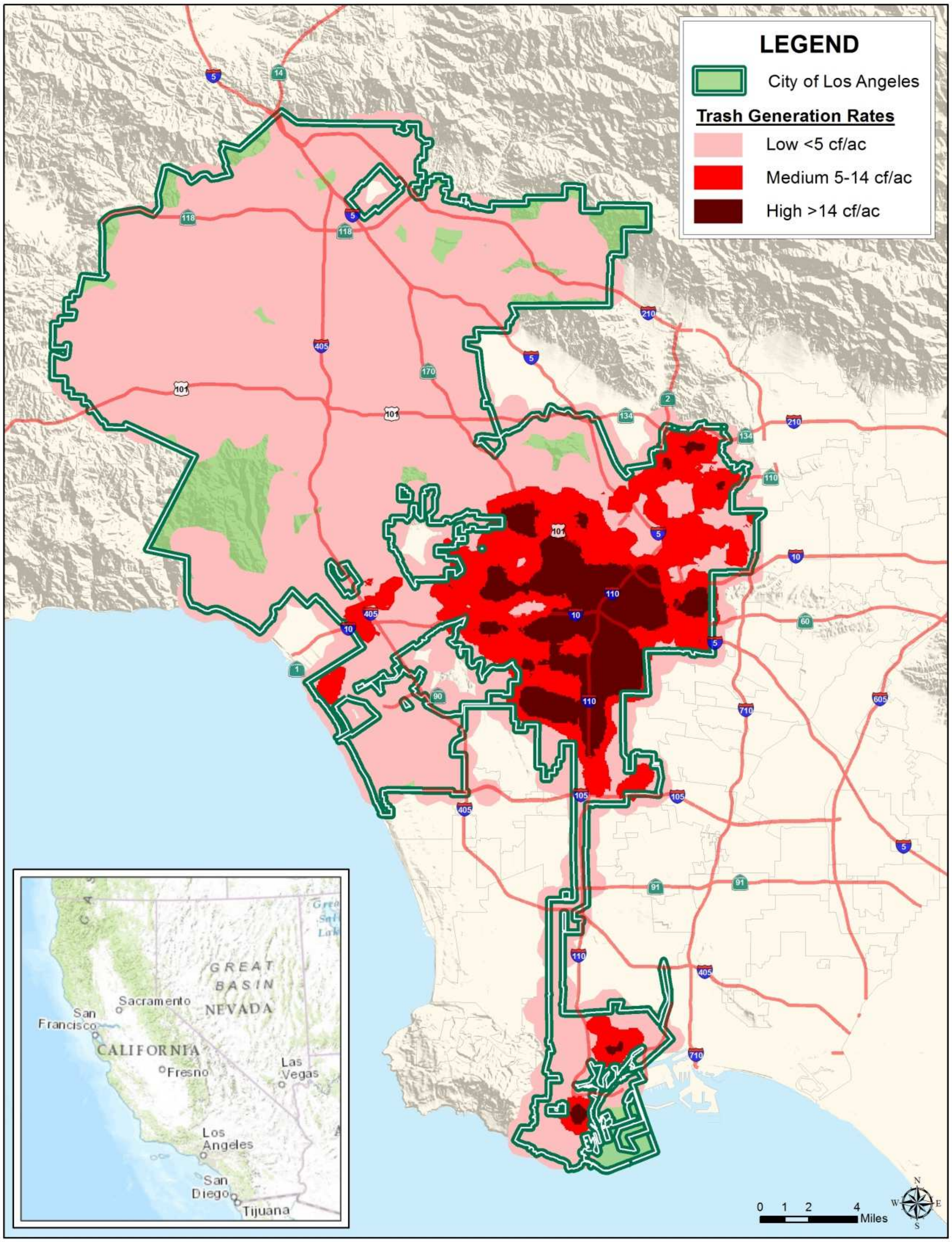

Figure 3.12. Trash accumulation rates in the City of Los Angeles region [Units of trash accumulation is in cubic feet per acre per Catch Basin Cleaning] (LA Sanitation - City of Los Angeles).

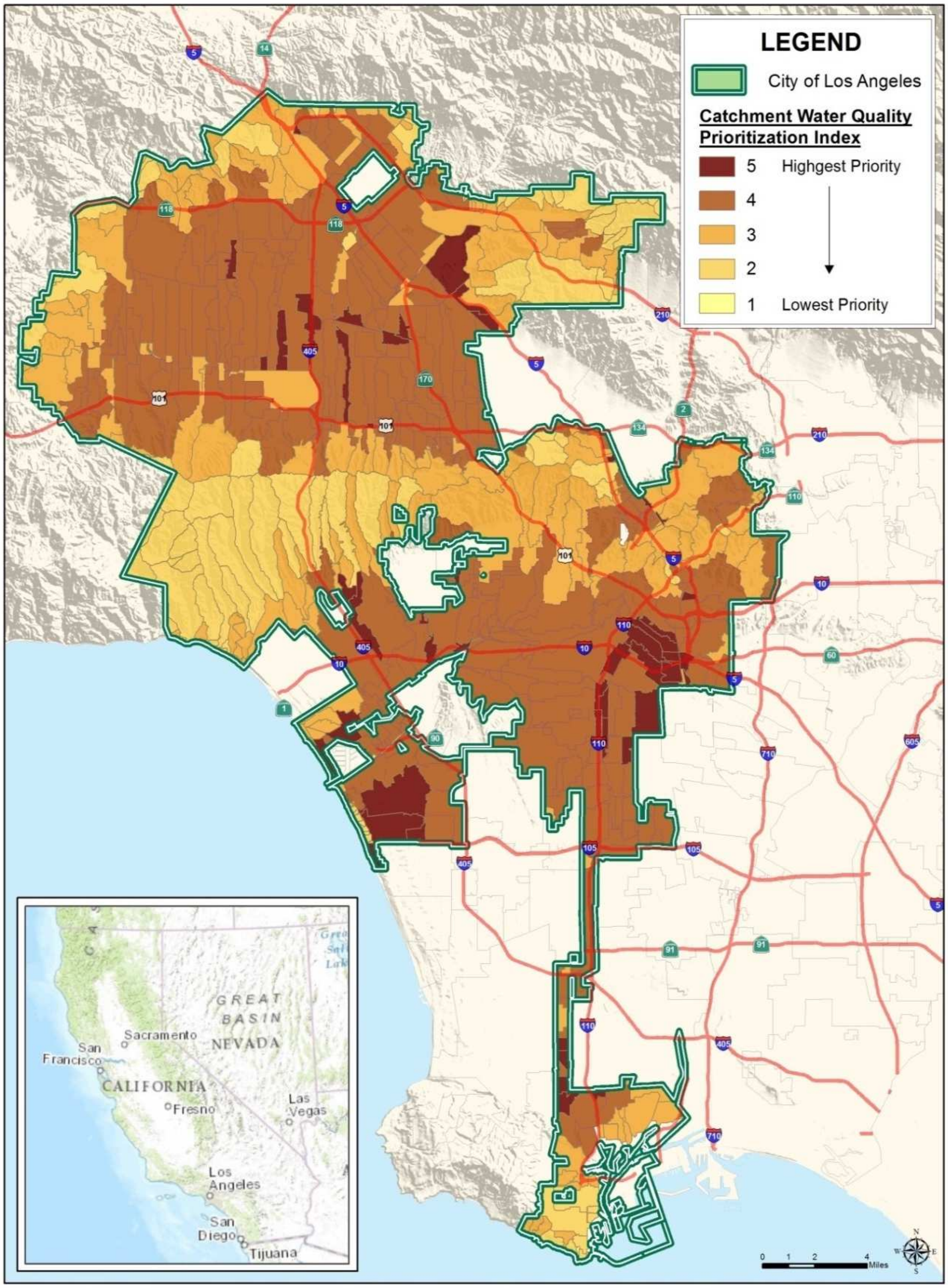

Figure 3.13. Boundaries of the City of Los Angeles [Catchment water quality prioritization index for the Los Angeles regional watersheds] (LA Sanitation - City of Los Angeles).

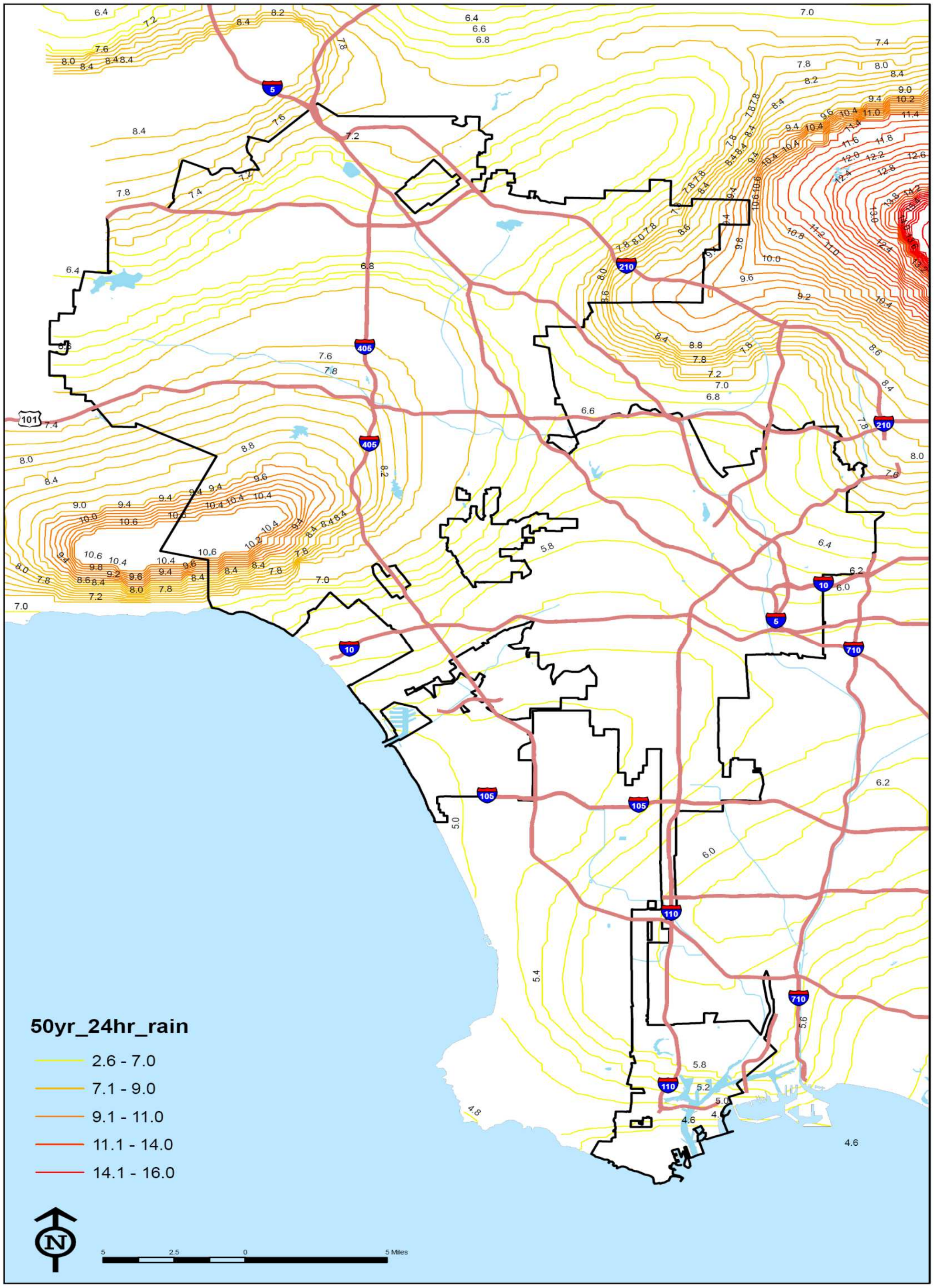

Figure 3.14. Boundaries of the City of Los Angeles (Los Angeles regional 50 year – 24 hour rain amounts in inches) (Rain Gauge Data, Los Angeles County).

4. LINEAR PROGRAMMING (LP) OPTIMIZATION METHOD FOR SELECTION AND SIZING SCMS

4.1 Optimal Selection and Sizing of SCMs

Following the assessment of stormwater quality vulnerability using the statistical-geographical method of Chapter 3 or other suitable method, selection and sizing of SCMs becomes a resource allocation problem. On the one hand, stormwater must meet TMDLs or other regulatory water-quality targets. On the other hand, there are finite resources to install, maintain, and replace SCMs. At the scale of stormwater control experienced in large cities, such as Los Angeles, stormwater management is a time-staged process. Areas must vulnerable to stormwater pollution must be identified and prioritized. Next, the network of SCMs and other stormwater control infrastructure (detention and conveyance) is expanded over time until the entire urban area is covered. At the same time, local building codes and ordinances must prescribe onsite stormwater control and improvement guidelines for new developments, public or private, so that stormwater protection is ensured simultaneously with new growth. In addition, SCMs that retain and filter stormwater must be maintained regularly, sometimes after every major storm. One example of the former type of frequent-maintenance SCMs is a catch basin that fills with trash. Another example is filtration media inside SCMs that become clogged with suspended solids, oil and grease, and bacterial growth.

4.2 Mathematical Models for Linear Programming (LP) SCM Selection and Sizing

This section describes a mathematical programming approach to SCM selection and sizing. The effective investment in SCMs constitutes a resource allocation problem where scarce capital, land, and skilled labor, are inputs to achieve costly flood control and water quality objectives (see, for example, Kalman et al., 2000; Strecker et al., 2001; Sample et al., 2001; USEPA, 2003; Zhen and Yu, 2004; Lee et al., 2005; City of Los Angeles, 2009B; Liu et al., 2014)). There are multiple SCMs and other management technologies (storm drains, treatment plants, reservoirs) available to control stormwater's quantity and quality (City of Los Angeles, 2009). Their deployment involves installation, operation, and maintenance costs. A large share of those costs stems from the number of SCMs and the geographic distribution needed to provide adequate coverage of the sources of multiple urban stormwater pollutants (Urbonas, 1995; Wong et al., 1997; Kalman et al, 2000; Sample et al., 2001; USEPA, 2003; Currier et al., 2004; Sim et al., 2011; Lee et al., 2012). Behera et al. (2006) presented a probabilistic analysis of urban stormwater quality. A decision support system (DSS) for reducing pollutant loads and the cost of best management practices (BMPDSS) implementation in the Sun Valley watershed (California) was reported by Tetra Tech (2007). The BMPDSS relied on the simulation program LSPC, by Shen et al. (2004), for predicting pollutants' loads at selected locations of a watershed (see also, Ackerman et al., 2005). The USEPA's Storm Water Management Model (SWMM) (USEPA, 2008) is widely used for simulating stormwater quantity and quality in urban settings (Oraei Zare et al., 2012). The USEPA's SUSTAIN (System for

Urban Stormwater Treatment and Analysis Integration) Model has SCM siting and performance appraisal capabilities (USEPA, 2009; Lee et al., 2012).

Several of the cited references dealing with SCMs applied simulation tools for predicting stormwater quantity and quality and assessing SCM performance, such as the SWMM (Oraei Zare et al., 2012), or SUSTAIN (Lee et al., 2012), or Geographic Information Systems (GIS) coupled with Decision Support Systems (DSS) (Sample et al., 2001). SCM performance has been commonly assessed in the pertinent literature by routing stormwater through SCM configurations and tracking its volume and quality along its downstream path.

This research work links stormwater quality and quantity characteristics with SCM selection and sizing within an optimization approach that considers (1) SCM design characteristics (geometry and structure), (2) water retention and water throughput capabilities of SCMs, (3) SCM water-purification capacity, (4) the cost of SCM implementation, operation and maintenance, (5) the hydrologic and soil characteristics of the areas covered by a network of SCMs, and (6) principles of Low Impact Development (LID) (Davis, 2005; Beyerlein, 2012; Tillinghast et al., 2012) applied to stormwater management by focusing on water-retaining SCMS. The linking of themes (1) and (6) to obtain globally optimal SCMs represents the novelty and contribution of this work to the field of stormwater management in urban areas. This research work's methodology aims at providing a practical tool for stormwater practitioners with several goals in mind. First, the methodology captures the basic stormwater management objectives, that is, the control of stormwater quality and quantity. Second, the methodology relies on fundamental principles of conservation of mass, cost considerations, and generally available or developable data with which to construct the optimization problems. Lastly, the methodology can be implemented in ubiquitous, widely accessible, software that does not require specialized training in optimization theory by practitioners well versed with SCMs.

The methodology for SCM sizing and selection developed in this work focuses on LID SCMs, such as vegetated swales, infiltration trenches, percolation wells, porous pavement (green streets and parking lots), detention basins (dry ponds), and other stormwater management technologies that (i) may retain a specified fraction of stormwater near its area of origin, and (ii) reduce the concentrations of pollutants in stormwater passing through SCMs. The methodology applies to single-event storms of specified durations that produce known quantities of runoff and concentrations of stormwater pollutants at specified locations within urban areas. The single-event approach is commonly used in the United States. Storm events of specified return interval and duration, say, 24-hour or 48-hour durations, are commonly used to calculate stormwater quantity and quality in management operations (California Regional Water Quality Control Board, 2014). The following sections present the methodology for SCM optimization and clarify its application with two examples.

4.2.1 Linear Programming (LP) Approach to SCMs and Stormwater Quality Management

Figure 4.1 shows an area where stormwater is generated with key elements that enter into the SCM sizing and selection problem. There are i = 1, 2, 3, …, n sites identified as possible locations for the deployment of SCMs, one per site. There is a volume of stormwater I_i, i = 1, 2, …, n., arriving at each of the n SCM sites. The influent storm runoff contains R indicator pollutants with concentrations C_{ir}, i = 1, 2, …, *n; r* = 1, 2, …, *R*. At each site *i* there are *j* = 1, 2, …, *J* possible SCMs to be installed, only one of which will be installed at each site. Part or all of the influent runoff goes through SCM j at site i, where some of it may be retained by the surrounding soil ($V_{retained}$), and the remainder may exit as flow-through volume with concentration E_{ijr}. If the influent stormwater (I_i) exceeds the capacity of a SCM to retain stormwater and pass flow through it, then a bypass volume is generated that joins the flow-through volume downstream from the SCM to form the effluent from the SCM. The volume of effluent from each SCM may be subject to regulatory maximum. It blends with unregulated storm runoff R_i, if any, originating between the SCM and the downstream location (monitoring station) where a TMDL or water-quality goal may be set by regulatory policy. There may be flood control regulations that impose maximum quantity of stormwater runoff at the monitoring station. The runoff R_i has concentration CR_{ir} of pollutant *r*. The concentration of the flow arriving at the monitoring station must be equal to or less than a specified TMDL or regulatory concentration goal.

Figure 4.2 shows a schematic of a SCM and the various volumes of stormwater associated with it during the single-event (design) storm of specified duration. I is the volume of stormwater arriving at the SCM during the design storm with concentration C of a specific pollutant of interest. $V_{through}$ denotes the volume of stormwater that passes through the SCM during the design storm. This is called the flow-through volume, which exits from the SCM with a concentration E of the pollutant of interest. $V_{retained}$ is the volume of water retained on site by the SCM during the design storm. This retained volume may be the result of percolation of captured stormwater by a SCM into the surrounding soil. At a minimum, it equals the internal water-holding capacity of a SCM, which fills up with stormwater during the design storm. V_{bypass} represents the volume of water that spills over the SCM, being neither retained nor passed through it, and has concentration C of the pollutant of interest. The evapotranspiration (ET) of any vegetation on a SCM is nil during the design storm.

In writing the water balance equation for a SCM as depicted in Figure 4.2, it is assumed that its internal water-holding volume fills with water during the design storm. The equality of input volumes and output volumes dictates that:

$$V_{bypass} = I - V_{retained} - V_{through} \tag{4.1}$$

Care must be taken to constrain the retained ($V_{retained}$) and flowthrough ($V_{through}$) volumes so that their sum does not exceed the input volume of stormwater (*I*). The volume of water retained by SCM of type *j* on site *i* is expressed by the following formula:

$$V_{retained,i,j} = a_{ij}\, K_{ij} + c_{ij} \tag{4.2}$$

i = 1, 2, 3, …, *n*; *j* = 1, 2, 3,…, *J*. The coefficients a_{ij} and c_{ij} are known characteristics of SCM *j* on site *i;* K_{ij}.denotes the unknown design dimension (or decision variable) of the SCM *j* on site i, which can be a length, or an area, or a volume, as elaborated upon below.

Some SCM, such as catch basins with filter media, are commonly not given credit for volume retention (Tetra Tech, Inc, 2010). In this case, $a_{ij} = 0$, and $c_{ij} = 0$ in equation (4.2). SCMs that have considerable surface storage capacity and are underlain by low-permeability soils or impervious materials are covered by equation (4.2) by setting $a_{ij} = 1$ and $c_{ij} = 0$ with K_{ij} representing the unknown storage volume. Other SCMs retain stormwater on site predominantly by percolation through the surrounding, permeable, soils. In this case, the determination of the coefficients a_{ij} and c_{ij} requires the consideration of the SCM geometry, the hydraulic properties of the surrounding soil, and the duration of percolation (equal to the duration of the design storm). To illustrate, consider a SCM j on site *i*, as depicted in Figure 4.2, and assume that the length and (unknown) width of its bottom surface are L_{ij} and W_{ij}, respectively. Stormwater percolates (vertically) during the duration of the design storm (Δ*t,* typically 24 or 48 hours) from the SCM through its bottom surface into the underlying soil, which has an infiltration capacity *f*. The volume of retained stormwater during the design storm equals:

$$V_{retained,i,j} = L_{ij} \cdot W_{ij} \cdot f \cdot \Delta t \tag{4.3}$$

so that $a_{ij} = L_{ij}\ f\ \Delta t$, $c_{ij} = 0$, and $K_{ij} = W_{ij}$ (the decision or design variable). Some SCMs, such as percolation wells, retain water by percolation to the soil surrounding its side and bottom surfaces. The analysis leading to their volume of retention is similar to that presented above after modification to account by the changed geometry of the percolation surface. Details of the volume-retaining equations for various SCMs can be found in section 4.7 of this chapter.

The flow-through volume in the *j*-th SCM *j* on site *i* is assumed to equal the release of a linear reservoir with effective storage V_{ij}. The linear release model is the most widely used among hydrologic/hydraulic release models for water-storage bodies (Amorocho, 1973), and adopted for subsurface layers in popular hydrologic models such as the Hydrologic Modeling System (HMS) (US Corps of Engineers, 2000). Therefore:

$$V_{through,i,j} = r_{ij} \cdot V_{ij} \cdot \Delta t \tag{4.4}$$

in which r_{ij} is the release coefficient (units of 1/time), which must be determined experimentally, and *Δt* is the duration of the design storm. The flow-through volume in equation (4.4) for SCM *j* on site *i* is rewritten as follows:

$$V_{through,i,j} = b_{ij}\, K_{ij} + d_{ij} \tag{4.5}$$

The (known) coefficients b_{ij} and d_{ij} are characteristics of the SCM j on site i. To illustrate, consider a SCM j on site i, whose effective storage is V_{ij}. The linear release model states that the temporal rate of volume change (= dV_{ij}/dt) equals $r_{ij} \cdot V_{ij}$. Therefore, written in finite-difference form, the flow-through volume is given by equation (4.5), with $b_{ij} = r_{ij}\,\Delta t$, $K_{ij} = V_{ij}$, and $d_{ij} = 0$. If, for example, the depth (D_{ij}) of a SCM is the design (unknown) dimension (or decision variable), and its width (W_{ij}) and length (L_{ij}) are known, then $b_{ij} = r_{ij} \cdot W_{ij} \cdot L_{ij} \cdot \Delta t$, and $K_{ij} = D_{ij}$. In the case of percolation wells the effective storage does not include the design variable (that is, the depth of the well), implying that $b_{ij} = 0$ and $d_{ij} = r_{ij}\,\Delta t\, V_{ij}$. Generally, the flow-through volume is minor compared with the retention and bypass volumes in SCMs that retain stormwater onsite. Further details about the calculation of the flow-through volume of SCMs are found in section 4.7 of this chapter.

The soil, aggregate, or filter media within a SCM reduces the concentration C_{ir} of the r-th pollutant in the input stormwater at the i-th site to a value E_{ijr} in the flow-through volume from the j-th SCM according to the following equation involving the treatment efficiency ξ_{ijr} ($0 < \xi_{ijr} < 1$) of the SCM j on site i with respect to stormwater pollutant r:

$$\xi_{ijr} = \frac{C_{ir} - E_{ijr}}{C_{ir}} \tag{4.6}$$

$i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, J$; $r = 1, 2, \ldots, R$; so that the concentration of pollutant r in the flow-through volume becomes:

$$E_{ijr} = C_{ir} \cdot \left(1 - \xi_{ijr}\right) \tag{4.7}$$

The change in the concentration of the r-th pollutant as it moves through a SCM is quantified by mass balance of stormwater and pollutant. For example, the mass $M_{I,i,r}$ of pollutant r in the volume of stormwater I with concentration $C_{i,r}$ arriving at site i equals:

$$M_{I,i,r} = I_i \, C_{ir} \tag{4.8}$$

$i = 1, 2, \ldots, n$; $r = 1, 2, \ldots, R$. The mass of pollutant r leaving the SCM j on site i depends on the volume of stormwater retained, on the flow-through volume, and on the treatment efficiency of the SCMs, as shown in a subsequent section. Equations (4.1)-(4.8) are the building blocks of the SCM optimization procedures presented in the next two sections.

4.2.2 Linear Programming (LP) Method for Optimal SCM Sizing

4.2.2.1 The Objective Function

The objective function of the LP method is to minimize the total cost of installing, operating, maintaining, and replacing SCMs at n sites. In this instance the type (j) of SCM to be installed at each site i is predetermined. The sizes of all the SCMs at the n sites must be found optimally. The SCM to be installed at the i-th site has an unknown capacity K_i, $i = 1, 2, \ldots, n$, and a unit variable cost of SCM capacity equal to P_i. This unit cost is the sum of the unit initial installation cost and the unit operational, maintenance, and replacement (OMR) cost expressed as a present value. The various SCMs may have different unit costs and service lives. P_i is calculated by converting the streams of costs for each SCM to a present value using the same discount rate and the same period of analysis using standard engineering economic principles. The capacity of a SCM may be expressed in units of volume, or treatment area, or as a treatment length. Percolation (dry) wells, for instance, may have standardized cross sectional areas, in which case the design variable is their depth of subsurface penetration. Other SCMs (say, infiltration trenches) may have two of their three dimensions (depth, width, length) standardized, and the third dimension unknown, in which case the unknown dimension becomes the decision variable. Some SCMs may be designed in terms of an area of treatment (such as porous pavement in parking lots). Detention ponds are commonly designed in terms of their storage capacity (say, in m^3). Consequently, the unit cost of SCM capacity (P_i), may be expressed in \$/volume, in \$/area, or as \$/length, to accommodate volumetric, areal, or longitudinal designs of SCMs, respectively, as the case might be.

The objective value of the LP method for SCM sizing is to minimize total cost of the SCMs at the *n* deployment sites:

$$Minimize\ Z = \sum_{i=1}^{n}(P_i \cdot K_i + F_i) \tag{4.9}$$

in which the minimization is with respect to the unknown SCM capacities, or decision variables, K_i; F_i denotes a fixed, and known, cost associated with the *i*-th SCM that is independent of its size. The objective function equation (4.9) may be subjected to various constraints, whose nature depends on the type of stormwater problem being addressed. The types of constraints that may arise are presented in general form next.

4.2.3 Capacity Constraints

The capacity of the SCM on site *i* may not exceed a maximum $K_{max,i}$ and must have a minimum size $K_{min,i}$:

$$K_{min,i} \leq K_i \leq K_{max,i} \tag{4.10}$$

i = 1, 2, …, *n.* The maximum and minimum capacities must be specified by the analyst. Notice that there are *n* capacity constraints equation (4.10), one for each SCM site.

4.2.4 Budgetary Constraint

The budgetary constraint, if applicable, states that the installation, operation, maintenance, and replacement cost of the n SCMs may not exceed a maximum available budget B. The budgetary constraint is as follows:

$$\sum_{i=1}^{n}(P_i \cdot K_i + F_i) \leq B \tag{4.11}$$

4.2.5 Feasibility Volumetric Constraints

It follows from mass balance that the volume of retained stormwater plus the volume of flow-through cannot exceed the volume of stormwater arriving at the SCM on site *i*:

$$V_{retained,i} + V_{through,i} \leq I_i \tag{4.12}$$

i = 1, 2, …, n. Dropping the sub-index j in equation (4.2), the volume of retained flow is expressed as follows:

$$V_{retained,i} = a_i\, K_i + c_i \tag{4.13}$$

Likewise, the flow-through volume in equation (4.5) simplifies to the following expression once the j sub-index is omitted:

$$V_{through,i} = b_i\, K_i + d_i \tag{4.14}$$

Using equations (4.13) and (4.14) in constraint equation (4.12) yields:

$$(a_i + b_i)\, K_i \leq I_i - (c_i + d_i) \tag{4.15}$$

i = 1, 2, …, n. The n equations (4.15) constitute the feasibility volumetric constraints, which are always required.

4.2.6 SCM-Specific, Performance-Volumetric Constraints

Many regulatory or permitting agencies limit the volume of stormwater (O_i) leaving site i. The SCM effluent O_i equals the sum of the bypass volume plus the flow-through volume at the SCM on site i. The bypass volume $V_{bypass,i}$ at the SCM on site i equals the stormwater volume I_i minus the sum of the retained stormwater plus the flow-through volume:

$$V_{bypass,i} = I_i - \left[V_{retained,i} + V_{through,i}\right] \tag{4.16}$$

Using equations (4.13) for the retained volume, and equation (4.14) for the flow-through volume in equation (4.16), the bypass volume is written as follows:

$$V_{bypass,i} = I_i - [\, K_i(a_i + b_i) + c_i + d_i] \tag{4.17}$$

i = 1,2, …, n. The bypass volume is, by virtue of equation (4.12), non-negative.

To obtain the volume of stormwater O_i immediately downstream from the SCM on site i one must add the bypass volume expressed by equation (4.17) to the flow-through volume in equation (4.14). The volume O_i is then:

$$O_i = V_{bypass,i} + V_{through,i} = I_i - (K_i\, a_i + c_i) \tag{4.18}$$

The n site-specific, performance-volumetric constraints specify that O_i may not exceed $O_{max,i}$, where the latter is the maximum value that the SCM effluent O_i may take at site i. The constraints are expressible as follows:

$$K_i\, a_i \geq I_i - O_{max,i} - c_i \tag{4.19}$$

i = 1, 2, …, n. Constraints equation (4.19) are sometimes re-written as requirements that the volume of stormwater retained at a site i be not less than a specified percentage of the incoming stormwater I_i. Constraints equation (4.19) may or may not be part of an LP sizing problem, depending on local regulations of stormwater volumes.

4.2.7 Constraints on Maximum Runoff at Arbitrary Locations

Referring to Figure 4.1, the location of the monitoring station could also be a runoff control station. The volume of stormwater Q at that location may be regulated to not exceed a maximum value Q_{max}. The flow Q equals the sum of the unregulated flows R_i plus the SCM effluents, O_i:

$$Q = \sum_{i=1}^{n} R_i + \sum_{i=1}^{n}\big(I_i - (K_i\, a_i + c_i)\big) \tag{4.20}$$

The volumetric constraint is written as follows:

$$\sum_{i=1}^{n} R_i + \sum_{i=1}^{n}\big(I_i - (K_i\, a_i + c_i)\big) \le Q_{max} \tag{4.21}$$

Equation (4.21) can be generalized to a situation where a set of unregulated flows identified by the index s = 1, 2, …, $n_R \le n$, and a set of SCM effluents identified by the index i = 1, 2, …, $n_O \le n$, converge at a common runoff control location v, v = 1, 2,…, $n_Q \le n$, where the allowable volume of stormwater equals $Q_{max,v}$. The corresponding constraints on maximum runoff are as follows, in standard linear programming (LP) format (with decision variables on the left-hand side of the constraint):

$$\sum_{i=1}^{n_O} K_i\, a_i \ge \sum_{s=1}^{n_R} R_s + \sum_{i=1}^{n_O}(I_i - c_i) - Q_{max,v} \tag{4.22}$$

v = 1, 2,…, n_Q. Notice that equation (4.22) is a subcase of equation (4.21) with n_Q =1, $n_O = n_R = n$. Constraints (4.22) may or may not be part of the LP sizing problem depending on local regulations.

4.2.8 Water-Quality Constraints

The concentration C of the stormwater volume accruing at the monitoring station in Figure 4.1 may not exceed a maximum value denoted by TMDL. The mass of pollutant r in the flow-through volume $K_i b_i + d_i$ on site i is:

$$M_{through,i,r} = (K_i b_i + d_i) \cdot E_{ir} \tag{4.23}$$

i = 1, 2, …, n; r = 1, 2, …, R. E_{ir} is the concentration of pollutant in the flow-through volume that passes through SCM j at site i. It is given by equation (4.7) after the index j is suppressed in that equation:

$$E_{ir} = C_{ir} \cdot (1 - \xi_{ir}) \tag{4.24}$$

In which ξ_{ir} represent the treatment efficiency of the SCM on site i with respect to pollutant r:

$$\xi_{ir} = \frac{C_{ir} - E_{ir}}{C_{ir}} \tag{4.25}$$

The mass of pollutant r in the flow-through volume takes the following form after substituting equation (4.24) in equation (4.23):

$$M_{through,i,r} = (K_i b_i + d_i) \cdot C_{ir} \cdot (1 - \xi_{ir}) \tag{4.26}$$

i = 1, 2, …, n; r = 1, 2, …, R.

The bypass volume $V_{bypass,i}$ on site i (given by equation (4.16)) has concentration C_{ir} equal to that of the inflow volume I_i. Therefore, the mass of pollutant r in the bypass volume of the SCM on site i is:

$$M_{bypass,i,r} = \{I_i - [K_i \cdot (a_i + b_i) + c_i + d_i]\} \cdot C_{ir} \tag{4.27}$$

i = 1, 2, …, n; r = 1, 2, …, R. The uncontrolled runoff R_i (if any) between site i and the TMDL control point (see Figure 4.1) carries a concentration of pollutant CR_{ir} in it and a mass of pollutant $M_{R,i,r}$ given by:

$$M_{R,i,r} = R_i \cdot CR_{ir} \tag{4.28}$$

i = 1, 2, …, n; r = 1, 2, …, R.

The mass in equation (4.28) is added to those expressed in equations (4.26) and (4.27) to give the mass M_{ir} of pollutant r arriving at the water-quality monitoring station from the SCM on site i and with the unregulated stormwater issuing between the same SCM and the monitoring station. The mass M_{ir} becomes, after algebraic simplifications:

$$M_{ir} = R_i \cdot CR_{ir} + I_i \cdot C_{ir} - (K_i\, a_i + c_i) \cdot C_{ir} - (K_i\, b_i + d_i) \cdot C_{ir} \cdot \xi_{ir} \tag{4.29}$$

i = 1, 2, …, n; r = 1, 2, …, R. It is convenient to consolidate separately in equation (4.29) the terms that involve the decision variables K_i and those that do not, as follows:

$$M_{ir} = S_{ir} - A_{ir} - K_i\, e_{ir} \tag{4.30}$$

In which:

$$S_{ir} = R_i\, CR_{ir} + I_i\, C_{ir} \tag{4.31}$$

$$A_{ir} = C_{ir} \cdot (c_i + d_i\ \xi_{ir}) \tag{4.32}$$

$$e_{ir} = C_{ir} \cdot (\, a_i + b_i\, \xi_{ir}) \tag{4.33}$$

i = 1, 2, …, n; r = 1, 2, …, R. The total mass of pollutant r arriving at the downstream TMDL control point from all upstream sites i = 1, 2, 3, …, n is obtained by adding the masses M_{ir} in equation (4.29)

$$M_r = \sum_{i=1}^{n} M_{ir} = \sum_{i=1}^{n} [S_{ir} - (\, A_{ir} + K_i\, e_{ir})] \tag{4.34}$$

r = 1, 2, …, R.

The concentration of pollutant r in stormwater arriving at the TMDL control point equals the total mass M_r expressed by equation (4.34) divided by the total volume Q given by equation (4.20). The concentration must be equal to or less than the TMDL for pollutant r, or $TMDL_r$:

$$\frac{M_r}{Q} \leq TMDL_r \quad or \;\; M_r \leq Q \;\cdot TMDL_r \tag{4.35}$$

$r = 1, 2, 3, \ldots, R$. Substituting equations (4.20) and (4.34) into equation (4.35), and simplifying the resulting expression, produces the R water-quality constraints:

$$\sum_{i=1}^{n} K_i \cdot q_{ir} \leq \sum_{i=1}^{n} (W_{ir} - \; v_{ir}) \tag{4.36}$$

$r = 1, 2, 3, \ldots R,$ in which:

$$q_{ir} = \; a_i \cdot TMDL_r - e_{ir} \tag{4.37}$$

$$v_{ir} = c_i \cdot TMDL_r - A_{ir} \tag{4.38}$$

$$W_{ir} = R_i \cdot (TMDL_r - CR_{ir}) + I_i \cdot (TMDL_r - C_{ir}) \tag{4.39}$$

The formulas for A_{ir} and e_{ir} are given in equations (4.32) and (4.33), respectively.

The solution of the LP problem comprising equation (4.9) (the objective function), subject to capacity constraints (equation (4.10)), budgetary constraint (equation (4.11)), feasibility volumetric constraints (equation (4.15)), SCM-specific, performance volumetric constraints (equation (4.19)), constraints on maximum runoff at arbitrary locations (equation (4.22)), and water-quality constraints (equation (4.36)) would yield the optimal sizes of the SCMs that meet all the capacity, budgetary, volumetric, and water-quality constraints. The solution, if it exists, is assured to be a global optimum. Some constraints, such as the budgetary constraint, may not be necessary in some applications. Likewise, there may be cases in which water-quality constraints may not apply. In other instances, some of the volumetric constraints (such as equations (4.22)) may not be needed. Recall, however, that the feasiblity volumetric constraints equation (4.15) are always necesarry in order to obtain correct results.

The next section describes an alternative optimization method that applies to situations in which the type of SCM to be deployed at at site i is unknown, but the sizes of SCMs are known, say, by using standardized designs. This gives rise to a binary linear integer programming (BLIP) method for SCM selection.

4.3 Binary Linear Integer Programming (BLIP) Method for Optimal SCM Selection

The BLIP approach is pertinent when SCMs such as percolation wells, catch basins, infiltration basins, or other, are built following standardized designs at each site. In this case the SCM capacities K_{ij} are known. The unknown (decision) variables are denoted by x_{ij}, a binary integer variable that takes the value 1 when the *j*-th type of SCM is selected for deployment at the *i*-th site, and takes the value equal 0 when the *j*-th type of SCM is not selected for deployment at the *i*-th site. The problem then becomes one of choosing the best type of SCM at each site i.

4.3.1 The Objective Function

The objective function minimizes the total cost of SCM deployment, in which F_{ij} is a fixed cost independent of the size of the SCM:

$$Minimize\ Z = \sum_{i=1}^{n} \sum_{j=1}^{J} x_{ij} \cdot \left(P_{ij}^{*} + F_{ij}\right) \tag{4.40}$$

where:

$$P_{ij}^{*} = P_{ij} \cdot K_{ij} \tag{4.41}$$

The SCM capacities K_{ij} are predetermined and conform to existing standards. The minimization in equation (4.40) is with respect to the binary, decision, variables x_{ij}.

4.3.2 One SCM Per Site

The following constraints guarantee that only one SCM is installed per site:

$$\sum_{i=1}^{J} x_{ij} \leq 1 \tag{4.42}$$

i = 1, 2, 3, …, *n;* and:

$$\sum_{i=1}^{n} \sum_{j=1}^{J} x_{ij} \geq n \tag{4.43}$$

4.3.3 Capacity Constraint

Capacity constraints are satisfied by the standardized design of the SCMs.

4.3.4 Budgetary Constraint

The total expenditure (present value) on SCMs may not exceed the amount *B:*

$$\sum_{i=1}^{n} \sum_{j=1}^{J} x_{ij} \cdot \left(P_{ij}^{*} + F_{ij}\right) \leq B \tag{4.44}$$

In some applications the budgetary constraint is not applied.

4.3.5 Feasibility Volumetric Constraints

These constraints require that the volume of stormwater retained plus the flow-through volume at the SCM on site i cannot exceed the available stormwater I_i (this generalizes equation (4.15)):

$$\sum_{j=1}^{J} x_{ij} \cdot a_{ij}^{*} \le I_i \tag{4.45}$$

$i = 1, 2, \ldots, n$; in which:

$$a_{ij}^{*} = a_{ij}K_{ij} + c_{ij} + b_{ij}K_{ij} + d_{ij} \tag{4.46}$$

The feasibility volumetric constraints are always required.

4.3.6 SCM-Specific, Performance-Volumetric Constraints

These constraints set limits on the volume of stormwater leaving the i-th SCM site (generalizes equation (4.19)):

$$I_i - \sum_{j=1}^{J} (K_i\, a_i + c_i) \cdot x_{ij} \le O_{max,i} \tag{4.47}$$

$i = 1, 2, \ldots, n$; equation (4.47) is re-written in standard LP format:

$$\sum_{j=1}^{J} (K_i\, a_i + c_i) \cdot x_{ij} \ge I_i - O_{max,i} \tag{4.48}$$

$i = 1, 2, \ldots, n$. Constraints (4.48) may or may not be part of the BLIP SCM selection problem, depending on local regulations on stormwater volume.

4.3.7 Constraints on Maximum Runoff at Specified Locations

These constraints are applicable when a set of unregulated flows R_s identified by the index $s = 1, 2, \ldots, n_R \le n$, and a set of SCM effluents O_i identified by the index $i = 1, 2, \ldots, n_O \le n$, coalesce at a common runoff control location v, $v = 1, 2, \ldots, n_Q \le n$, where the allowable volume of stormwater equals $Q_{max,v}$. The corresponding constraints on maximum runoff are as follows (this generalizes equation (4.22)):

$$\sum_{i=1}^{n_O}\left[\sum_{j=1}^{J}\left(K_{ij}\ a_{ij}+c_{ij}\right)\cdot x_{ij}\right] \geq \sum_{s=1}^{n_R} R_s + \sum_{i=1}^{n_O} I_i - Q_{max,v} \tag{4.49}$$

$v = 1, 2, \ldots, n_Q$. Constraints equation (4.49) may or may not be part of the BLIP SCM selection problem, depending on local regulations on stormwater volume.

4.3.8 Water-Quality Constraints

These constraints do not allow the concentration of the *r*-pollutant to exceed the regulatory concentrations at the water-quality monitoring station. These equations are derived from the fundamental inequality that relates M_r, Q, and $TMDL_r$, which denote the total mass of pollutant *r*, the total volume of stormwater, and the regulatory concentration of pollutant *r* at the monitoring station, respectively (see equation (4.35)):

$$M_r \leq Q\ \cdot TMDL_r \tag{4.50}$$

$r = 1, 2, 3, \ldots, R$; in which the total volume *Q* of stormwater at the water-quality monitoring station is obtained by generalizing equation (4.20):

$$Q = \sum_{i=1}^{n} R_i + \sum_{i=1}^{n}\sum_{j=1}^{J} x_{ij}\ \cdot\left[I_i - \left(K_{ij}\ a_{ij} + c_{ij}\right)\right] \tag{4.51}$$

The mass of pollutant *r* arriving at the water-quality monitoring station from the *i*-th site where the SCM *j* is installed and with the unregulated stormwater issuing between the same SCM site and the water-quality monitoring station equals:

$$M_{ir} = M_{R,i,r} + \sum_{j=1}^{J}\left(M_{through,i,j,r} + M_{bypass,i,j,r}\right)\cdot x_{ij} \tag{4.52}$$

The mass of pollutant *r* in the flow-through volume is (this generalizes equation (4.26)):

$$M_{through,i,j,r} = \left(K_{ij} b_{ij} + d_{ij} \right) \cdot C_{ir} \cdot \left(1 - \xi_{ijr}\right) \tag{4.53}$$

The mass of pollutant *r* in the bypass volume equals (this is a generalization of equation (4.27)):

$$M_{bypass,i,j,r} = \left\{ I_i - \left[K_{ij} \cdot \left(a_{ij} + b_{ij}\right) + c_{ij} + d_{ij} \right] \right\} \cdot C_{ir} \tag{4.54}$$

The total mass arriving at the water-quality monitoring station from all stream SCM sites and unregulated areas is obtained by summing M_{ir} in equation (4.52) over all i sites (generalizes equation (4.34)):

$$M_r = \sum_{i=1}^{n} M_{R,i,r} + \sum_{i=1}^{n} \left[\sum_{j=1}^{J} \left(M_{through,i,j,r} + M_{bypass,i,j,r} \right) \cdot x_{ij} \right] \tag{4.55}$$

The substitution of equations (4.51) and (4.55) in equation (4.50), followed by algebraic simplification, yields the *R* water quality constraints at the monitoring station:

$$\sum_{i=1}^{n} \sum_{j=1}^{J} x_{ij} \cdot \left(K_{ij} \cdot q_{ijr} + v_{ijr} \right) \leq \sum_{i=1}^{n} W_{ir} \tag{4.56}$$

r = 1, 2, 3, … *R;* in which:

$$q_{ijr} = a_{ij} \cdot TMDL_r - e_{ijr} \tag{4.57}$$

$$e_{ijr} = C_{ir} \cdot \left(a_{ij} + b_{ij}\, \xi_{ijr} \right) \tag{4.58}$$

$$\xi_{ijr} = \frac{C_{ir} - E_{ijr}}{C_{ir}} \tag{4.59}$$

$$v_{ijr} = c_{ij} \cdot TMDL_r - A_{ijr} \tag{4.60}$$

$$A_{ijr} = C_{ir} \cdot \left(c_{ij} + d_{ij}\, \xi_{ijr} \right) \tag{4.61}$$

$$W_{ir} = R_i \cdot (TMDL_r - CR_{ir}) + I_i \cdot (TMDL_r - C_{ir}) \tag{4.62}$$

The solution of the BLIP objective function equation (4.40), subject to one-SCM-per-site constraints equations (4.42)-(4.43), budgetary constraint equation (4.44), feasibility volumetric constraints equation (4.45), SCM-specific performance volumetric constraints equation (4.48), constraints equation (4.49) on maximum runoff at specified locations, and water quality constraints equation (4.56) would produce the optimal selection of SCMs at the n deployment sites. Some applications may not require all of the constraints. The feasibility volumetric constraints equation (4.45) are always necessary, however.

4.4 Example 1: LP Method for Optimal SCM Sizing

4.4.1 General Description

The first example illustrates the LP method for SCM sizing. Figure 4.3 shows the plan view of an area 500 m long and 300 m wide where there are five sites where SCMs will be installed (thus, i = 1, 2, 3,4, 5).

The SCMs in Figure 3 are intended to capture stormwater and reduce TN (total nitrogen: ammonia, nitrate, particulate organic nitrogen, and soluble organic nitrogen) concentration in stormwater so that a TMDL of maximum 45 g/m^3 is achieved at the control point downstream of the 500 m x 300 m area. The concentration of TN in input stormwater at the SCMs and in unregulated stormwater equal C_i = CR_i = 90 g/m^3, i = 1,2, 3, 4, 5. Site 1 is a section of a street where an infiltration trench SCM overlain by porous pavement will be placed. Sites 2 and 3, within a recreational area, will be occupied by vegetated swales with permeable granular soil. Sites 4 and 5 are dedicated to percolation wells downslope from the street transect and recreational areas. The SCMs will be designed for a rainfall event of 2.50 cm falling in (Δt) = 48 hours. 60% of the area is impervious with a runoff coefficient K = 1, and 40% is pervious with a runoff coefficient K = 0.5. These conditions produce a runoff equal to 3000 m^3 within the area under study (calculated with a rainfall / runoff model). Table 4.1 shows SCM data. Runoff and concentration data are presented in Table 4.2. Note that volume retention is not an explicit objective in this example. Instead, the objective is to minimize the cost of SCM implementation and meeting water quality goals at the TMDL station.

Table 4.3 summarizes the retention (a_{ij}, c_{ij}) and flow-through coefficients (b_{ij},d_{ij}) that enter in the volumetric balance of the SCMs considered in this example. The total budget for the SCM project is $ 4 million.

4.4.2 Results from the LP SCM Sizing Method

The data shown in Tables 4.1, 4.2, and 4.3 were used in the LP sizing method for SCMs described by objective function equation (4.9), capacity constraints equation (4.10), budgetary constraint equation (4.11), feasibility volumetric constraints equation (4.15), and water-quality constraint equation (4.36). The resulting LP problem was input as a spreadsheet and solved with the package SOLVER in EXCEL. Table 4.4 shows the optimized SCM sizes and other pertinent performance data.

The value of the stormwater concentration at the monitoring control station equals C = 45 g/m^3, the maximum allowed. Notice that, in addition to meeting the water-quality objective, the SCMs capture 74% (or 2,225 m^3) of the total stormwater volume I = 3000 m^3 The total of SCMs equals $ 3,403,949, less than the $ 4 million available budget.

4.5 Example 2: BLIP Method for SCM Selection

4.5.1 General Description

The BLIP method for SCM selection was applied to the selection of two types of SCMs: percolation wells and catch basins, to be deployed on the perimeter of a boulevard to meet stormwater-retention regulation, water-quality requirements, and a budgetary constraint. The storm-retention regulation is that the sum of the stormwater volumes retained by the SCMs must be at least 25% of the total stormwater input to the SCMs. The water-quality requirement states that the concentration *C* of stormwater runoff at the TMDL does not exceed 45 g/m^3 of total suspended solids (TSS). The available budget for SCM deployment equals \$ 250,000. The design storm has depth of 5.0 cm falling in Δt = 48 hours over a 100 % impervious areas. The boulevard is 300 m long and 30 m wide, and the catchment area includes an additional 50 m x 30 m upslope and downslope from the SCM-deployment area. This produces 600 m^3 of stormwater from the design storm, to which 15 m^3 of unregulated flow are added in this example. Figure 4.4 shows a schematic of the geometric configuration of the study site. At each of the eight corners shown on Figure 4.4 either a percolation well or a catch basin with filter media will be deployed to remove total suspended TSS from stormwater. Note that there are i = 1, 2, 3, …, n = 8 sites in this example. In the following notation, x_{i1}, and x_{i2}, denote catch basin and percolation wells, respectively, that is, j = 1 for catch basins, and j = 2 for percolation wells. x_{i1}= 0 if a catch basin is not selected at the *i*-th site, and it equals 1 if it is selected at a site; x_{i2}= 0 if a percolation well is not selected at the *i*-th site, and it equals 1 if it is selected at a site.

The percolation wells and catch basins have standardized sizes in this instance due to site characteristics. The percolation wells have a diameter ϕ = 1 m and length L = 15 m. The catch basins have width W = 1.5 m, effective depth D = 2 m, and length L = 3 m. Catch basins do not retain stormwater on site because their perimeter walls are built of impervious materials. Table 4.5 presents data on the SCMs. Table 4.6 contains data on stormwater volumes and concentrations. Table 4.7 summarizes the volumetric data for the SCMs.

4.5.2 Results from the BLIP Method for SCM Selection

The BLIP problem consists in this instance on the objective function equation (4.40), which minimizes the cost of SCM implementation plus various constraints, subject to one-SCM-per site constraints equations (4.42)-(4.43), budgetary constraint equation (4.44), feasibility volumetric constraints equation (4.45), water-quality constraints equation (4.56), and the minimum stormwater-retention constraint (must retain at least 25% of the stormwater input equal to 600 m^3), which is written as follows:

$$\sum_{i=1}^{n=8}\sum_{j=1}^{J=2} x_{ij} \cdot V_{retained,i,j} = \sum_{i=1}^{n=8}\sum_{j=1}^{J=2} x_{ij} \cdot \left(a_{ij}\, K_{ij} + c_{ij}\right) \geq 150 \quad \text{m}^3 \qquad (4.63)$$

Constraint equation (4.63) is a variant of the constraint equation (4.49) on maximum runoff. In addition, the water quality constraint equation (4.56), establishes that the TSS concentration *C* at the downstream TMDL site may not exceed 45 g/m^3. The solution of the BLIP problem so stated would produce the optimal selection of SCMs at the *n* deployment sites. The BLIP problem was coded as a spreadsheet input (with data from Tables 4.5, 4.6, and 4.7) and solved with the package SOLVER in EXCEL.

The optimal solution is to install two percolation wells and six catch basins. Because (i) the wells and catch basins are standardized, (ii) the input of stormwater, and (iii) the TSS concentrations are equal at each site and in the unregulated flow, the two percolation wells can be installed at any one of the eight possible sites, and the same holds true for the locations of the six catch basins, provided that only one SCM is installed at each site. Table 4.8 summarizes the performance characteristics of the optimized SCM network.

The results of Table 4.8 indicate that the optimized selection of SCMs in this example meets the water-quality, water retention, and budgetary constraints. Specifically, the TSS concentration at the TMDL control point equaled 37.2 g/m^3, below the maximum 45 g/m^3. The retained inflow equaled 30.7 % of the total inflow, which exceeded the minimum target retention of 25 %. Finally, optimized total cost of SCM implementation ($171,388) was much less than the available budget ($250,000).

4.6 Linear Programming Conclusion

Two optimization methods were developed and presented in this work: one for optimal sizing of SCMs, and the other for optimal selection of SCMs. The former relies on a linear programming (LP) formulation. The latter uses a binary (0,1) linear integer programming (BLIP) formulation. The two optimization methods minimize the total cost of SCM deployment while satisfying constraints on (i) the total cost of deployment, (ii) SCM capacities, (iii) volumetric balance at SCM sites, (iv) stormwater volumes at arbitrary sites, and (v) water-quality at monitoring locations. The LP and BLIP methods are generic in their formulations and can be applied to various types of SCMs. An appealing trait of the LP and BLIP methods is that globally optimal solutions, if they exist, can be obtained with the SOLVER package in the ubiquitous software EXCEL.

This research presented a methodology aimed at aiding stormwater practitioners with real-world problems. Our methodology is being successfully tested in the City of Los Angeles, which manages close to 50,000 SCMs for stormwater control in an urban area extending over 1,225 km^2 with 28,000 km of streets. Two examples were presented in this research to illustrate the application of the LP and BLIP methodologies. The two examples were successfully solved after a detailed step-by-step formulation, showing that our methodology can be implemented to size and select SCM to meet stormwater quantity and quality objectives. Further research will tackle the development of a general methodology to solve for the optimal size and type of SCMs at chosen deployment sites simultaneously, which requires the solution of a nonlinear programming problem.

4.7 Hydrologic/Hydraulic Characteristics of Selected SCMs for Linear Programming

4.7.1 Volumetric Balance for Infiltration Trenches

Infiltration trenches are placed parking lots covered with porous pavement, some streets, and sidewalks. Stormwater infiltrates through the pavement and enters a gravely bed of uniform depth D_T below the porous pavement, unknown width W, and length L as shown on Figure 4.5. The trench depth D_T typically varies between half a meter and one meter. The width W and length L of the infiltration trench are limited by the width and length of the porous pavement under which it lies. A perforated pipe is placed at the bottom of the trench with its centerline at depth D below the porous pavement. The infiltration trench saturates with stormwater and leaks water to the underlying soil as vertical percolation through its bottom area equal to W x L. Losses of water from the infiltration trench through its sides are neglected because it is assumed that infiltration is occurring around the trench vertically through porous pavement.

Let f denote the infiltration rate in m/hr through the soil beneath the trench, Δt be the duration of the design storm for which the trench is designed. The volume of water retained by the infiltration trench, $V_{retained}$, is given by the following formula(W is the width):

$$V_{retained} = f \cdot \Delta t \cdot W \cdot L = a\,W \tag{4.64}$$

in which the coefficient a is:

$$a = f \cdot \Delta t \cdot L \tag{4.65}$$

If the infiltration rate f = 0.00254 m/hr, Δt = 48 hours, and L = 500 m then $a \cong 61$ m^2. Notice that equation (4.64) is written in terms of the unknown width W of the infiltration trench.

The flow-through volume ($V_{through}$) of the infiltration trench is carried by the perforated pipe to daylight at a downstream point. The mechanism of water release from the infiltration trench is assumed to be that of a linear reservoir of effective volume V whose change in volume ΔV by water release is:

$$\frac{\Delta V}{\Delta t} = k\,V \tag{4.66}$$

where k is the linear-reservoir coefficient, whose dimensions are inverse time. This coefficient must be determined experimentally. Therefore $V_{through} = \Delta V = \Delta t \cdot k \cdot V$. The effective volume V in this case is $V = D \cdot L \cdot W \cdot v$, where v denotes the porosity of the gravel filling the infiltration trench. The volume through the infiltration trench takes the following form:

$$V_{through} = \Delta t \cdot k \cdot D \cdot L \cdot W \cdot v = b \cdot W \tag{4.67}$$

in which $b = \Delta t \cdot k \cdot D \cdot L \cdot v$. If Δt = 48 hours, D = 1 m, L = 500 m, k = 0.007 hr^{-1}, v = 0.30 then $b \cong 50$ m^2.

The sum of the retained stormwater volume plus the flow-through volume in an infiltration trench must be less than the runoff I accruing to the infiltration trench:

$$V_{retained} + V_{through} = (a+b)\,W \leq I \tag{4.68}$$

which amounts to 111 $W \leq I$ using the values a and b calculated above.

4.7.2 Volumetric Balance for Percolation Wells

A simplified schematic of a percolation well is shown on Figure 4.6. A percolation well retains water by releasing water to the surrounding soil through its lateral surface area and through its bottom area. The bottom of the dry well must be above the highest possible level of the phreatic surface. Let f denote the infiltration rate in the soil surrounding the percolation well, Δt the duration of the design storm, ϕ the well diameter, D the depth of the outlet pipe that releases the flow-through volume from the percolation well, L the unknown active length of the percolation well (this is the length of the well filled with gravel of porosity v), I the stormwater volume that flows into the well. The volume of runoff retained by the percolation well is:

$$V_{retained} = \pi \cdot \phi \cdot L \cdot f \cdot \Delta t + \frac{\pi \phi^2}{4} f \cdot \Delta t \qquad (4.69)$$

Equation (6) is rewritten in the standard form as a function of the unknown well length L:

$$V_{retained} = a \cdot L + c \qquad (4.70)$$

in which:

$$a = \pi \cdot \phi \cdot f \cdot \Delta t \qquad (4.71)$$

and:

$$c = \frac{\pi \phi^2}{4} f \cdot \Delta t \qquad (4.72)$$

Letting f = 0.0127 m/hr, Δt = 48 hours, ϕ =1 m, produces a = 1.91 m^2, c = 0.48 m^3.

The flow-through volume in a percolation well is modeled as the release of a linear reservoir whose volume is in this instance equal to the effective well volume located above the outlet pipe. Therefore:

$$V_{through} = D \cdot \frac{\pi\,\phi^2}{4} \cdot v \cdot k \cdot \Delta t = d \qquad (4.73)$$

Notice that in this case $V_{through}$ is independent of the decision variable, L, therefore, $b = 0$. Setting $D = 1$ m, $\Delta t = 48$ hours, $\phi = 1$ m, v (porosity = 0.30, and $k = 0.069$ hr^{-1}, yields $d = 0.79$ m^3).

The values of *a, c*, *d* for the percolation well calculated above establish that:

$$V_{retained} + V_{through} = 1.91 \cdot L + 1.27 \leq I \qquad (4.74)$$

4.7.3 Volumetric Balance for Vegetated Infiltration Swales

Figure 4.7 shows a schematic of a vegetated infiltration swale and stormwater volumes pertinent to its volumetric balance. Vegetated infiltration swales retain and treat stormwater. The swale's soil must be permeable, and so must be the underlying soil that captures the precipitation that infiltrates through the swale. A perforated pipe is laid at a depth D_s at the bottom of the swale to remove excess moisture to downstream daylight. The volume of stormwater retained by a vegetated infiltrated swale amounts to the volume of water it can infiltrate during the duration of the design storm:

$$V_{retained} = f \cdot \Delta t \cdot A = a \cdot A \qquad (4.75)$$

where $a = f \cdot \Delta t$. An infiltration rate $f = 0.0127$ m/hr acting over the duration of the design storm equal to $\Delta t = 48$ hours leads to a retained volume of stormwater equal to 0.61 A (with $a = 0.61$ m).

The mechanism of water by flow-through volume in a vegetated infiltration swale is that of a linear reservoir:

$$V_{through} = \Delta t \cdot k \cdot D_s \cdot A \cdot v = b \ \cdot A \tag{4.76}$$

where $b = \Delta t \cdot k \cdot D_s \cdot v$. Setting Δt= 48 hours, D_s = 1 m, k = 0.0075 hr^1, and v = 0.3 implies that $b \cong$ 0.11 m, and a flow-through volume equal to 0.11 A.

The sum of the retained volume plus the flow-through volume in a vegetated infiltration swale must be less than the runoff I accruing to the SCM:

$$V_{retained} + V_{through} = (a + b)\ A \leq I \tag{4.78}$$

which amounts to 0.72 $A \leq I$ using the values a and b calculated above.

4.7.4 Volumetric Analysis for Catch Basins

Catch basins are not given retention credit because of their limited size and they have an impervious enclosure. Figure 4 shows a schematic of a catch basin.

Thus, $V_{retained}$ = 0, so that $a_{i1} = c_{i1} = 0$, i = 1, 2, …, n = 8. The flow-through volume is determined using the linear-volume release approach. Therefore:

$$V_{through} = \Delta t \cdot k \cdot L \cdot D \cdot W \cdot v = b \cdot K \tag{4.79}$$

where $b = \Delta t \cdot k \cdot v$, and $K = L \cdot D \cdot W$. Setting Δt= 48 hours (the storm duration), D = 2 m, L = 3 m, W = 1.5 m, k = 0.20 hr^1, and v = 0.5 implies that b_{i1} = 4.8 m^2, d_{i1} = 0, i = 1, 2, …, n = 8, and K = 9.0 m^3. Therefore, $V_{through}$ = 4.8 x 9.0 = 43.2 m^2.

Table 4.1. SCM data (ξ denotes the treatment efficiency of SCMs)

SCM	variable cost	Fixed cost	K_{max}	K_{min}	ξ
	(P_i)	(F_i, \$)			
inf. trench:1 (500 long)	\$ 250,000/m	1500	20 m (width)	3 m (width)	0.75
veg. swale: 2	\$ 800/m^2	1800	10000 m^2 (area)	1000 m^2 (area)	0.85
veg. swale: 3	\$ 800/m^2	1800	10000 m^2 (area)	1000 m^2 (area)	0.85
perc. well: 4	\$ 1570/m	4600	20 m (depth)	10 m (depth)	0.70
perc. well: 5	\$ 1570/m	4600	20 m (depth)	10 m (depth)	0.70

Table 4.2. Runoff and concentration data for the SCM sizing problem.

Variable	Volume	Concentration	
	m^3		g/m^3
I_1	381	C_1	90
I_2	1219	C_2	90
I_3	1219	C_3	90
I_4	50	C_4	90
I_5	50	C_5	90
R_1	31	CR_1	90
R_2	25	CR_2	90
R_3	25	CR_3	90
R_4	0	CR_4	90
R_5	0	CR_5	90
TMDL	--	C	45

Table 4.3. Values of the volumetric coefficients for the SCMs

SCM: Number	a_{ij}	b_{ij}	c_{ij}	d_{ij}
inf. trench:1	61 m^2	50 m^2	0	0
veg. swale: 2	0.61m	0.11 m	0	0
veg. swale: 3	0.61 m	0.11 m	0	0
perc. well: 4	1.91 m^2	0	0.48 m^3	0.79 m^3
perc. well: 5	1.91 m2	0	0.48 m^3	0.79 m^3

Table 4.4. Optimized results from the LP method for sizing SCMs.

SCM	Optimal size	cost ($)	$V_{retained}$ (m^3)
inf. trench:1	3 m (wide)	751,500	183
veg. swale: 2	1693 m^2 (area)	1,356,244	1033
veg. swale: 3	1528 m^2 (area)	1,224,205	932
perc. well: 4	20 m (deep)	36,000	39
perc. well: 5	20 m (deep)	36,000	39
ALL SCMs		**3,403,949**	**2,225**

Table 4.5. SCM data (ξ : treatment efficiency; v : porosity of fill material)

SCM	Variable cost	Fixed cost	Volume	v	ξ
	(P_i)	(F_i, $)	(K_{ij}, m^3)		
catch basins	$ 1900/m^3	900	9.0	0.50	0.95
perc. wells	$ 1806/m	4600	11.775	0.40	0.85

Table 4.6. Runoff and concentration data for the SCM selection problem.

Variable	Volume	Concentration	
	m^3		g/m^3
I_i, $i = 1,2,\ldots, 8$	75	C_i	90
R	15	CR	90
TMDL for TSS	--	C	45

Table 4.7. Values of the volumetric coefficients for the SCMs

SCM	a_{ij}	b_{ij}	c_{ij}	d_{ij}	$V_{retained,i,j}$	$V_{through,i,j}$
catch basins (j=1)	0	4.8 m^2	0	0	0	43.2 m^3
perc. wells (j=2)	6.029 m^2	0	1.51 m^3	3.77 m^3	91.94 m^3	3.77 m^3

Table 4.8. Optimized results from the BLIP method for SCM sizing.

Criterion	Total cost ($)	$V_{retained}$ (m^3)	Concentration C at TMDL point (g/m^3)
optimized	171,388	184	37.2
constraint	< 250,000	>150	<45

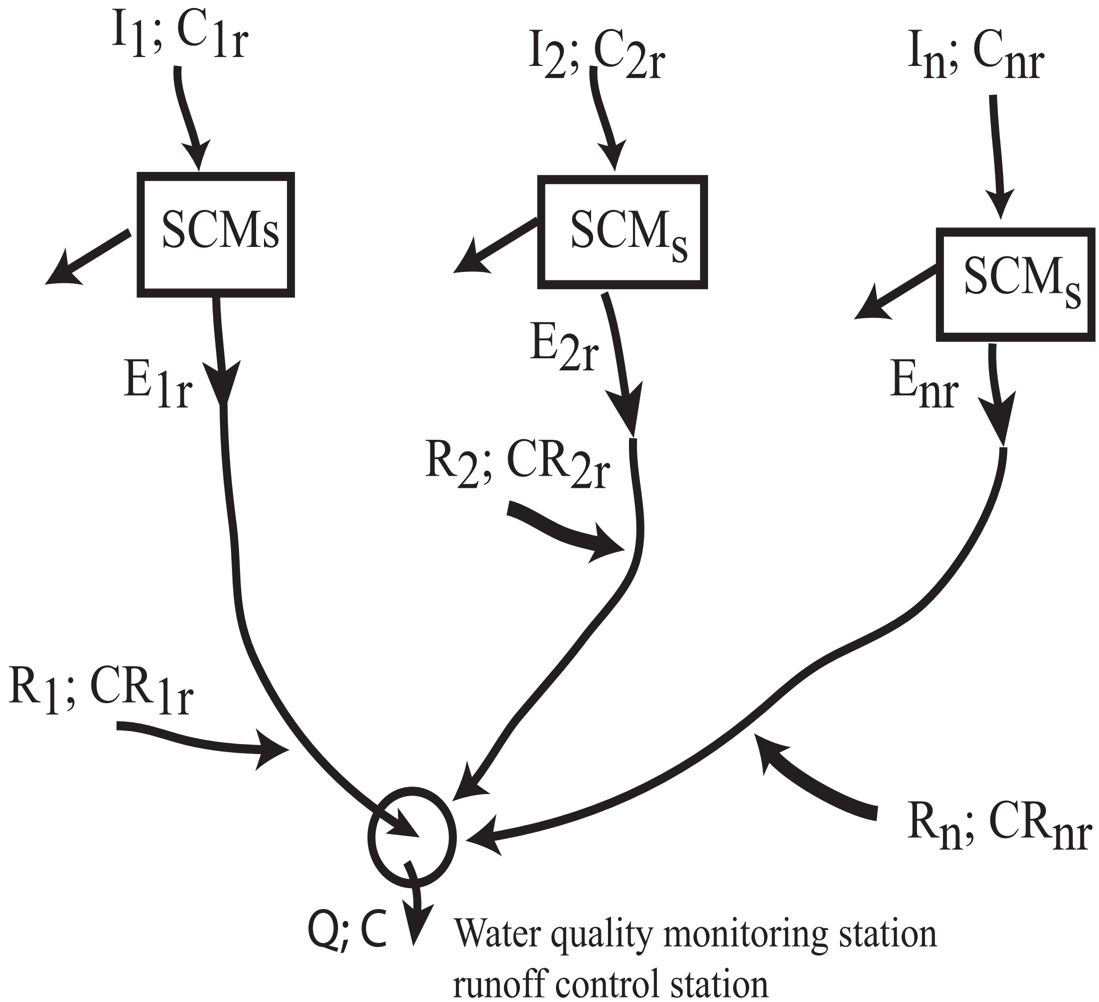

Figure 4.1. Key components of the LP SCM optimization problem. Plan view.

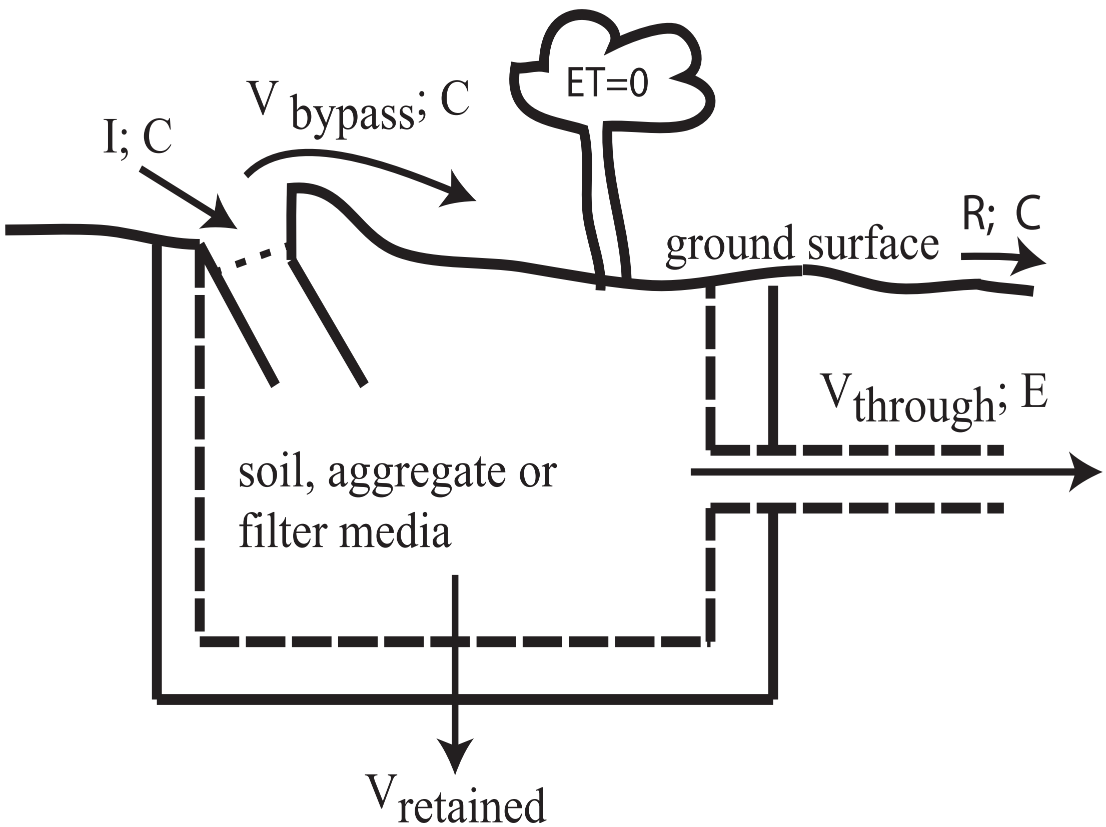

Figure 4.2. Schematic of a typical SCM with stormwater volumes and concentrations.

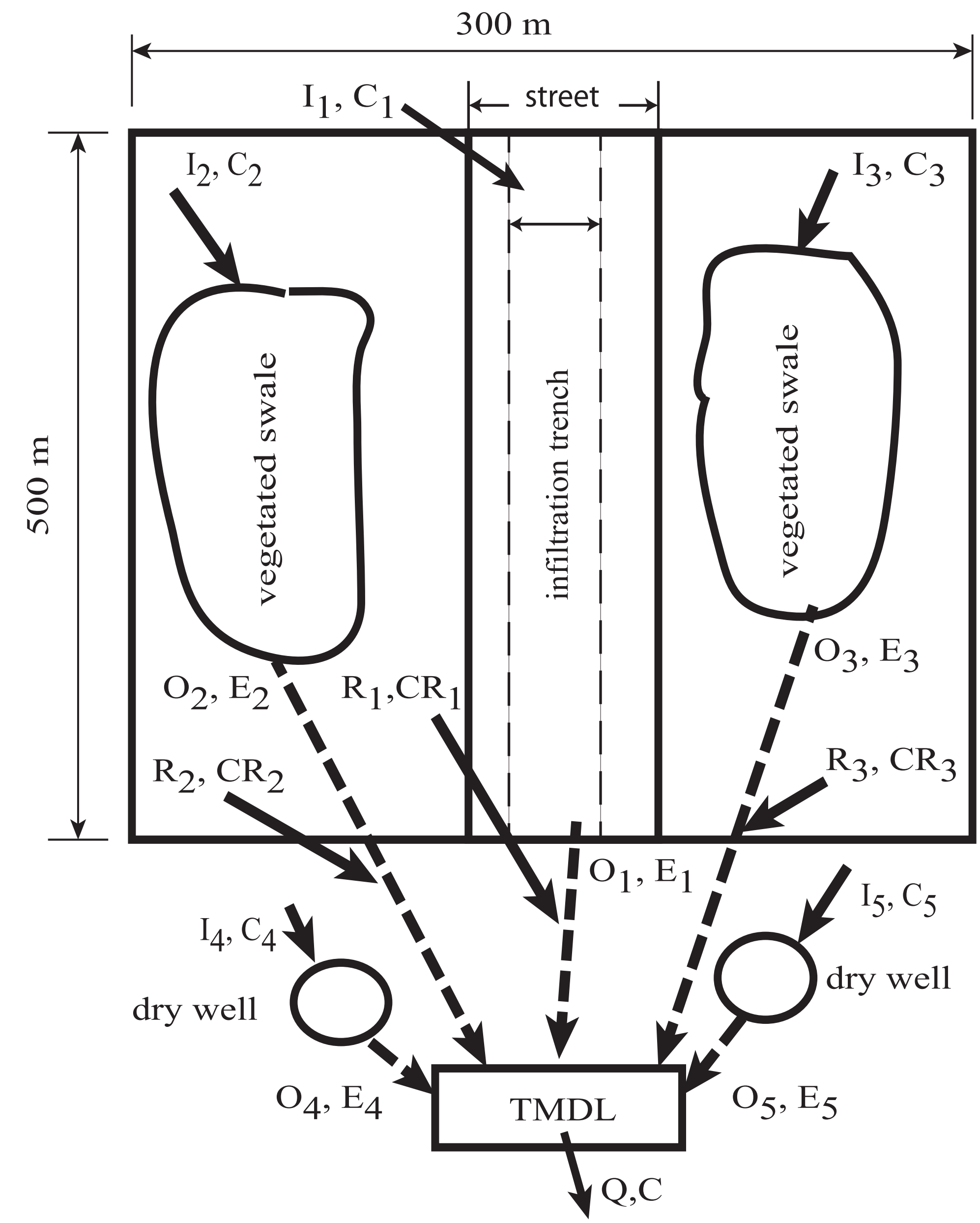

Figure 4.3. Plan view of area for installation of SCMs. Not drawn to scale.

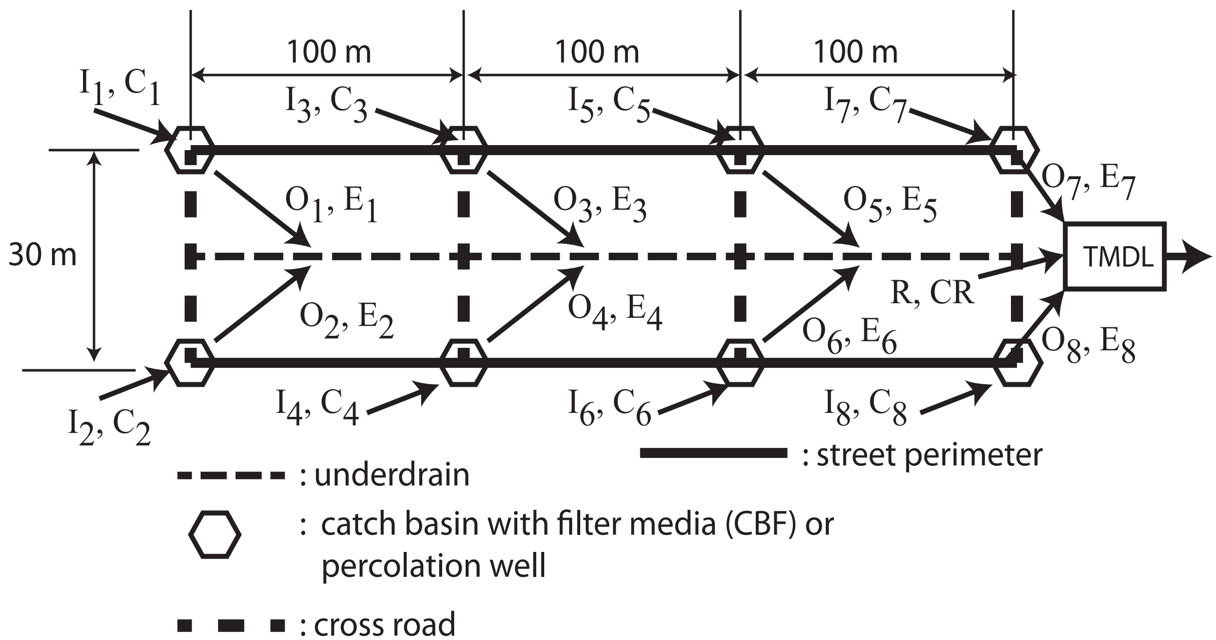

Figure 4.4. Sketch of the boulevard and site locations for SCMs. Plan view, not drawn to scale.

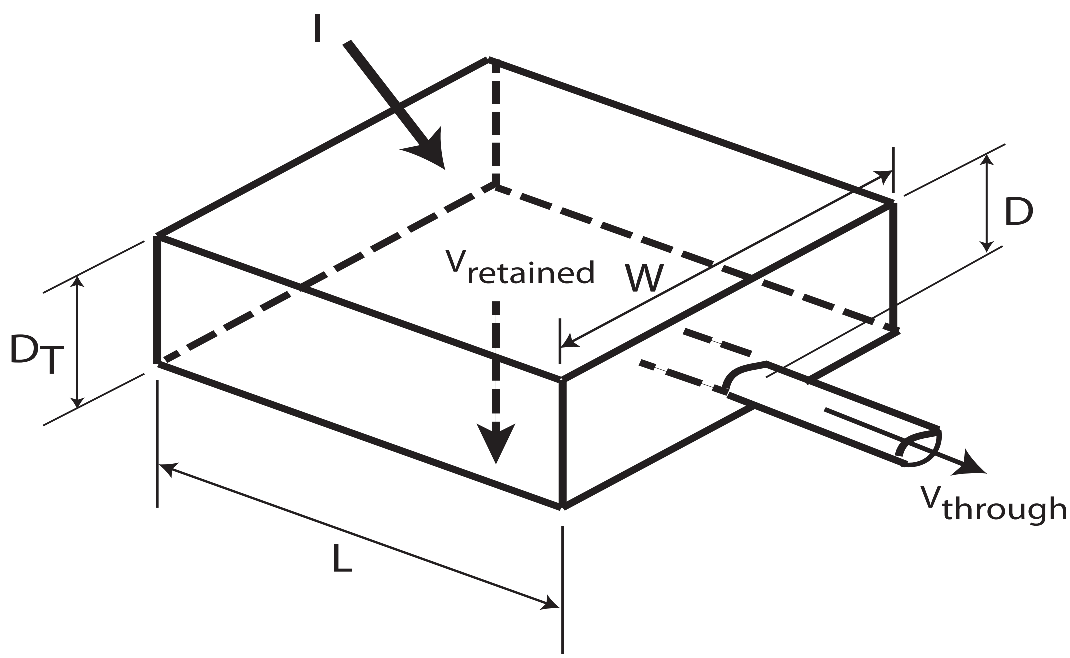

Figure 4.5. Schematic of an infiltration trench. Figure Not Drawn to Scale.

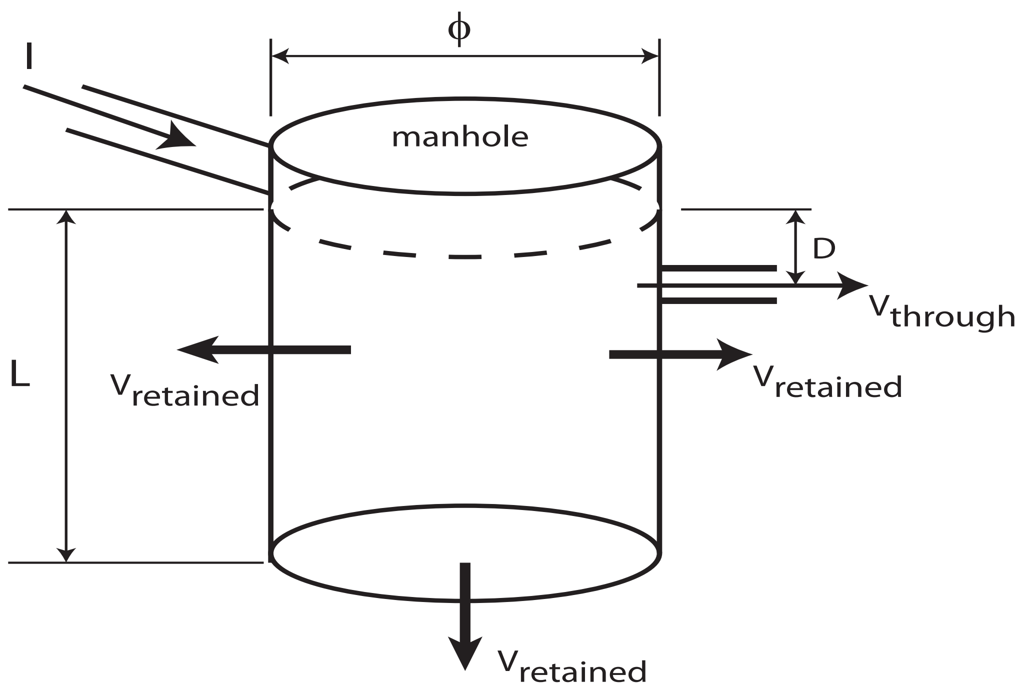

Figure 4.6. Percolation well and main intervening variables. Elevation view, not drawn to scale.

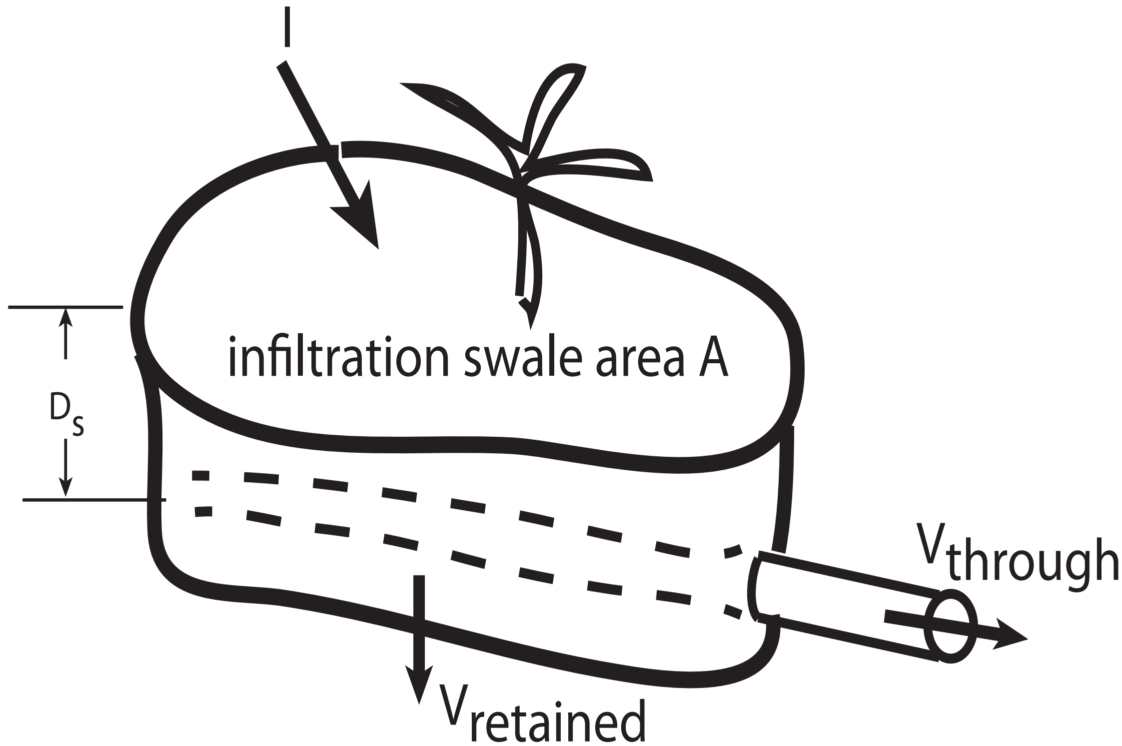

Figure 4.7. Schematic of a vegetated infiltration swale.

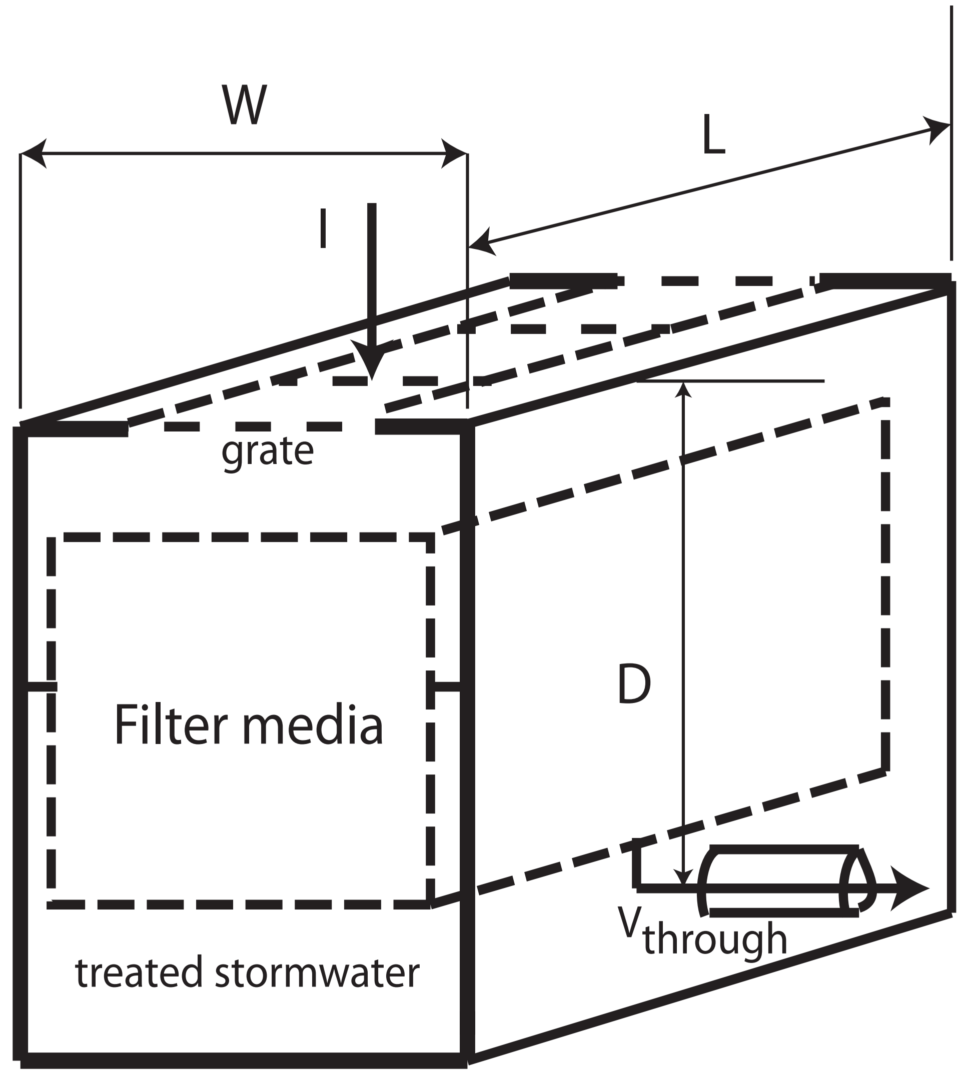

Figure 4.8. Sketch of a catch basin with filter media. There is no stormwater retention.

5. NONLINEAR PROGRAMMING (NLP) OPTIMIZATION METHOD FOR SELECTION AND SIZING SCMS

5.1 Optimal Selection and Sizing of SCMs

Following the assessment of stormwater quality vulnerability using the statistical-geographical method of Chapter 3 or other suitable method, selection and sizing of SCMs becomes a resource allocation problem. In Chapter 4 the Linear Programming (LP) method was introduced. This chapter will provide the information for the Nonlinear Programming (NLP).

5.2 Mathematical Models for Nonlinear Programming SCM Selection and Sizing

The following sections describe a novel Nonlinear Programming (NLP) method for the optimal selection and sizing of SCMs in urban areas. The method incorporates the key factors that govern the allocation of scarce resources to control stormwater threats, namely, cost minimization, reduction of urban flooding (by stormwater retention), improvement of stormwater quality, and basic design features of SCMs. Integration of the key SCM-governing factors, coupling the selection and sizing of SCMs, and providing a solution technique easily accessible to those concerned with managing stormwater constitute the novelty and contribution of this work. The NLP method generalizes from Chapter 4 on the subject matter of SCM design using linear programming (LP) methodology where the selection of the best types of SCMs was decoupled from their optimal sizing. Other optimization and simulation/optimization approaches applied to urban stormwater management can be found in the technical literature (see, for example, *Zhen et al.,* 2004; *Lee et al*., 2005; *Lee et al.,* 2012; *Oraei Zare et al*., 2012).

5.3 Methodology

5.3.1 The key Variables that Govern Stormwater Control with SCMs

A network of SCMs considered for deployment is depicted in Figure 5.1. There are i = 1, 2, 3, …, n sites identified as possible locations for the deployment of SCMs, one per site. There is storm runoff arriving at each of the n SCM sites with a volume I_i, i = 1, 2, …, n. The influent stormwater contains R indicator pollutants with concentrations C_{ir}, i = 1, 2, …, n; r = 1, 2, …, R. At each site i there are j = 1, 2, …, J possible SCMs to be installed, only one of which will be installed at each site. Some of the volume of influent stormwater at SCM j on site i is retained there (V_{Rij}), and some flows through the SCM and exits with a flow-through volume V_{Tij} and concentration E_{ijr}. Some of the influent stormwater may be bypassed (V_{Bij}) due to SCM capacity limitations. The flow-through volume blends with the bypassed volume immediately downstream of the SCM. There may be regulations on the allowed amount of flow-through volume plus bypass volume at any SCM, as well as on its water-quality characteristics. The sum of flow-through volume and retained volume blends with unregulated stormwater R_i originating between the SCM at site i and the downstream monitoring station where a water-quality or quantity requirement may be set by regulatory policy. The unregulated stormwater R_i has concentration CU_{ir} of pollutant r.

The concentration C of the total flow Q at the monitoring station may be subjected to regulatory requirements, such as a total maximum daily loads (TMDLs) on some of the pollutants in stormwater. Q may also by be regulated at the monitoring station by limiting its magnitude at that location. The NLP method is developed to select and size SCMs to cope with single-event, design storms specified by local regulations on stormwater management. These storms are usually 24 to 48 hours in duration and have specified precipitation depths (*City of Los Angeles,* 2009). The design-storm approach to SCM implementation is widely used in stormwater management (*Loáiciga et al.,* 2014).

Figure 5.2 depicts a generic cross-section of a percolation well, used to exemplify the various volumes that enter in the NLP formulation of SCM optimization. Figure 5.2 also shows the various volumes of stormwater generated at SCM j on site i during the duration of a single-event storm. The diameter, the column of water at full capacity, and the depth of the flow-through drain are the design dimensions of a percolation well, denoted by ϕ_{ij}, L_{ij}, and D_{ij}, respectively, and are shown in Figure 5.2. Other SCM have various other geometric characteristics. See *Loáiciga et al.* (2014) for a review of SCMs and the information for the analysis of various SCMs are in section 5.9. I_i denotes the volume of stormwater arriving at the SCM with a concentration C_{ir}. V_{Tij} is the volume of stormwater that passes through the SCM, or flow-through volume, if any, with concentration E_{ijr}. V_{Rij} represents the volume of water retained on site by the SCM, if any. V_{Rij} commonly include percolation of captured stormwater into the surrounding soil, as shown in Figure 5.2, as well as retention of stormwater within the SCM. At a minimum, V_{Rij} it equals the internal water-storing capacity of a SCM, which fills during the design storm. V_{Bij} denotes the volume of stormwater with concentration C_{ir} that bypasses the SCM, being neither passed through it nor retained on site. R_i and CU_{ir} denote the unregulated stormwater downstream of the SCM and its concentration, respectively. The unregulated volume of stormwater blends with the bypass and flow-through volumes. The fluxes shown on Figure 5.2 are instrumental in developing the NLP method described next.

5.4 The Objective Function of the Nonlinear Programming Method for SCM Sizing and Selection

The objective function of the NLP method is to minimize the present value of the total cost of installing, operating, maintaining, and replacing SCMs at n sites each with one SCM. A SCM j = 1, 2, …, J, at a site i = 1, 2, …, n has a to-be-determined design dimension K_{ij}, and a known unit cost of SCM capacity P_{ij}. This unit cost is the sum of the unit initial installation cost and the unit operational, maintenance, and replacement (OMR) cost expressed as a present value of all the costs that arise from installation and over the service lives of SCMs. The design dimension (a decision variable) of a SCM is expressed in units of volume (say, m^3, for example), or treatment area (m^2), or treatment length (units of length), depending on the type of SCM. Percolation (dry) wells typically feature standardized cross sectional areas, in which case the design variable is their depth of subsurface penetration. Other SCMs (say, infiltration trenches) may have standardized depths, in which case the unknown design variable is their surface area. Some SCMs may be designed in terms of their volumetric capacity. Detention basins are a case in point, in which the unknown design variable is the volume of the SCM. Therefore, the unit cost P_{ij} may be expressed as $/$m^3$, or as $/$m^2$, or as $/m to accommodate volumetric, areal, or longitudinal designs, respectively. In addition, there may be (known) fixed costs F_{ij} unrelated to the size of a SCM. The latter costs are present values in a manner analogous to the unit costs P_{ij}. A binary decision variable x_{ij}= 1 if SCM j is chosen at site i, or x_{ij}= 0 if the SCM j is not chosen at site i. There is one SCM at each possible deployment site. The possible sites i for SCM deployment are sites where stormwater and water-quality constraints are imposed. The objective of the NLP problem is the minimization of the total cost of SCM implementation (the function Z), whose decision variables are the binary variables x_{ij} and the design (real-valued) dimensions K_{ij}:

$$Minimize\ Z = \sum_{i=1}^{n} \sum_{j=1}^{J} \left(P_{ij} \cdot K_{ij} \cdot x_{ij} + x_{ij} \cdot F_{ij} \right) \quad (5.1)$$

The objective function equation (5.1) of the NLP problem involves the product of the decision variables K_{ij} and x_{ij}. It is a nonlinear objective function of a special nature due to the presence of the binary variables.

5.4.2 Constraints of the Nonlinear Programming Problem

5.4.2.1 One SCM Per Site

Each site must have one SCM. This is accomplished by means of two constraints. The first one ensures that there is not more than one SCM per site:

$$\sum_{i=1}^{J} x_{ij} \leq 1 \qquad i = 1, 2, 3, \ldots, n \quad (5.2)$$

The second constraint ensures that there is at least one SCM at each site:

$$\sum_{i=1}^{n} \sum_{j=1}^{J} x_{ij} \geq n \quad (5.3)$$

Constraints equations (5.2) and (5.3) combined ensure that there will be exactly one SCM at each site.

5.4.3 Capacity Constraints

The design variable of a SCM may not exceed a maximum K_{ijmax}, and must have a minimum size K_{ijmin}:

$$K_{ijmin} \leq K_{ij} \leq K_{ijmax} \qquad i = 1, 2, \ldots, n; j = 1, 2, \ldots, J \qquad (5.4)$$

5.4.4 Budgetary Constraint

The budgetary constraint states that the installation, maintenance, and replacement cost of SCMs may not exceed an allocated budget B:

$$\sum_{i=1}^{n} \sum_{j=1}^{J} \left(P_{ij} \cdot K_{ij} \cdot x_{ij} + x_{ij} \cdot F_{ij}\right) \leq B \qquad (5.5)$$

5.4.5 Volumetric Constrain

The first set of volumetric constraints imposes feasibility of water balance at SCM j on site i. These constraints require that the volume of retained stormwater (V_{Rij}) plus the flow-through volume (V_{Tij}) must not exceed the volume of stormwater I_i arriving at site i. V_{Rij} equals the design variable of the SCM times a (known) retention factor a_{ij}, to which a constant c_{ij} is also added, or $V_{Rij} = a_{ij}\, K_{ij} + c_{ij}$. The water-retention factor a_{ij} and constant a_{ij} are known characteristics of the SCM j at site i (see section 5.9). The flow-through $V_{Tij} = b_{ij}\, K_{ij} + d_{ij}$. The (known) flow-through factor b_{ij} and constant d_{ij} are characteristics of the SCM j at site i (see section 5.9). The set of volumetric feasibility constraints is written as follows:

$$\sum_{j=1}^{J} x_{ij} \cdot \left(a_{ij}K_{ij} + c_{ij} + b_{ij}K_{ij} + d_{ij}\right) \leq I_i \qquad i = 1, 2, \ldots, n \qquad (5.6)$$

The difference I_i – $[(a_{ij} + b_{ij})\, K_{ij} + c_{ij} + d_{ij}]$ equals the bypass volume V_{Bij}. The type of SCM deployed at site *i* is unknown, therefore the bypass volume at the *i*-th SCM site is written as a function of the binary variables x_{ij} as follows:

$$V_{Bi} = \sum_{j=1}^{J} x_{ij} \cdot \{I_i - [\, K_{ij}(a_{ij} + b_{ij}) + c_{ij} + d_{ij}]\} \qquad i = 1, 2, \ldots, n \tag{5.7}$$

The runoff O_{ij} immediately downstream from the SCM *j* at site *i* equals the sum of the bypass volume plus the flow-through volume. The effluent volume O_{ij} may be subjected to a constraint on maximum storm runoff (Q_{imax}) allowed immediately downstream of site *i*. This generates the following set of volumetric constraints immediately downstream of site *i*:

$$O_i = \sum_{j=1}^{J} x_{ij} \cdot [I_i - (K_{ij}\, a_{ij} + c_{ij})] \leq Q_{imax} \qquad i = 1, 2, \ldots, n \tag{5.8}$$

Adding the flows $O_i + R_i$ over all sites *i* yields the total flow *Q* accruing to the water-quality and quantity monitoring station (see Figure 5.1):

$$Q = \sum_{i=1}^{n} R_i + \sum_{i=1}^{n} \sum_{j=1}^{J} x_{ij} \cdot [I_i - (K_{ij}\, a_{ij} + c_{ij})] \tag{5.9}$$

In some instances the total flow *Q* may not exceed a maximum value Q_{max} at the runoff monitoring station (this is a total volumetric constraint):

$$Q = \sum_{i=1}^{n} R_i + \sum_{i=1}^{n} \sum_{j=1}^{J} x_{ij} \cdot [I_i - (K_{ij}\, a_{ij} + c_{ij})] \leq Q_{max} \tag{5.10}$$

5.4.6 Water-Quality Constraints

The mass of a pollutant *r* in storm runoff arriving at site *i* equals $M_{ir} = I_i\, C_{ir}$. The mass of pollutant *r* in the flow-through volume is $(K_{ij} b_{ij} + d_{ij}) \cdot E_{ijr}$. E_{ijr} is the concentration of pollutant *r* in the flow-through volume that passes through SCM *j* at site *i*. Part of the pollutant *r* is removed from flow-through by the SCM *j* at site *i* according to the following equation in which ξ_{ijr} is the pollutant *r* removal efficiency of SCM *j* at site *i* ($0 \leq \xi_{ijr} \leq 1$):

$$\xi_{ijr} = \frac{C_{ir} - E_{ijr}}{C_{ir}} \qquad i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, J;\ r = 1, 2, \ldots, R \quad (5.11)$$

Therefore, the concentration of the flow-through volume becomes:

$$E_{ijr} = C_{i,r} \cdot \left(1 - \xi_{ijr}\right) \quad i = 1, 2, 3, \ldots, n;\ j = 1, 2, 3, \ldots, J;\ r = 1, 2, 3, \ldots, R \quad (5.12)$$

The mass of pollutant *r* in the flow-through volume becomes:

$$Q_{ijr} = \left(K_{ij} b_{ij} + d_{ij}\right) \cdot E_{ijr} = \left(K_{ij} b_{ij} + d_{ij}\right) \cdot C_{ir} \cdot (1 - \xi_{ijr}) \quad (5.13)$$

$i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, J;\ r = 1, 2, \ldots, R.$

The bypass volume V_{Bij} at site *i* has concentration C_{ir} equal to that of the inflow volume I_i, and, thus, carries a mass of pollutant *r* equal to $V_{Bij} \cdot C_{ir}$. Adding the masses of stormwater pollutant *r* carried by bypass, flow-through, and unregulated volumes yields the mass G_{ijr} of the pollutant arriving at the water-quality monitoring station from SCM *j* at site *i* and from the area between this SCM and the downstream water-quality monitoring station. The masses G_{ijr} are added over all SCM types *j* and all sites *i* to produce the total mass G_r of pollutant *r* arriving at the water-quality monitoring station from all upstream sites $i = 1, 2, 3, \ldots, n$:

$$G_r = \sum_{i=1}^{n} \left[S_{ir} - \sum_{j=1}^{J} x_{ij} \cdot \left(A_{ijr} + K_{ij}\, e_{ijr} \right) \right] \quad (5.14)$$

$r = 1, 2, \ldots, R.$

in which:

$$S_{ir} = R_i\, CR_{ir} + I_i\, C_{ir} \quad (5.15)$$

$$A_{ijr} = C_{ir} \cdot \left(c_{ij} + d_{ij}\ \xi_{ijr}\right) \quad (5.16)$$

$$e_{ijr} = C_{ir} \cdot \left(a_{ij} + b_{ij}\, \xi_{ijr}\right) \quad (5.17)$$

The concentration of pollutant *r* in stormwater arriving at the water-quality monitoring station equals the total mass G_r expressed by equation (5.14) divided by the total volume Q given by equation (5.9). The concentration must be equal to or less than the water-quality constraint for pollutant *r*:

$$G_r \leq Q \cdot TMDL_r \qquad r = 1, 2, 3, \ldots, R \tag{5.18}$$

The R water-quality constraint equation (5.18) are explicitly defined after replacing Q with equation (5.9) and G_r with equation (5.14).

5.5 Summary of the Nonlinear Programming Method

The objective function is the minimization of SCM costs given by equation (5.1), whose decision variables are the binary variables x_{ij} and SCM design dimensions K_{ij}. The objective function is subject to one-SCM-per site constraints (equations (5.2) and (5.3), always required), SCM capacity constraints (equations (5.4), always required), budgetary constraint (equation (5.5), may or may not be applicable), volumetric feasibility constraints (equations (5.6), always required), volumetric constraints immediately downstream of SCM sites (equations (5.8), may or not be applicable), maximum runoff constraint at the runoff monitoring station (equation (5.10), may or may not be applicable), and water quality constraints (equations (5.18), may or may not be applicable). Other constraints could be added to meet area-specific idiosyncrasies.

5.6 Application of the Nonlinear Programming Method

5.6.1 Project Characteristics

Figure 5.3 shows the general location of the Glenoaks stormwater capture project in the City of Los Angeles, California. The drain system of the City of Los Angeles, California, features 2,414 km of pipes and 161 km of open channel. The stormwater control system in Los Angeles includes about 38,000 screened catch basins and thousands of other SCMs. Los Angeles' average daily dry weather and wet-weather runoffs are approximately 189,250 m^3 and 38,022,800 m^3, respectively (City of Los Angeles, 2009B, 2014). The Glenoaks stormwater capture project covers a tributary drainage area equal to 122.21 ha (ha = hectare, 1 ha = 10,000 m^2). The 48-hour, design storm for stormwater management in the study area has a depth equal to 1.91 cm. The amount of runoff generated by the design storm in the study area equals 13,504 m^3. The soil underlying the project area is a sandy loam with infiltration rate equal to 0.0254 m/hr. This permeable soil is suitable for SCMs that retain stormwater by seepage into the soil. The focus pollutant in this example is suspended solids (SS) emanating from erosion of the foothills north of the study area.

Figure 5.4 shows a map of the Glenoaks project. Most of the storm runoff generated within the project area flows southerly towards the Glenoaks and Sunland boulevards. Stormwater moves along the Glenoaks boulevard from its northwestern, upstream, end to its southeastern, downstream, end (from left to right on Figure 5.4). The length of the boulevard in the Glenoaks project is close to 2400 m. The potential SCMs considered for deployment in this example are: percolation wells (PW, on the two curbs of the boulevard, one on each curb), grassy swales (GS, on the sidewalks next to the boulevard, one on each sidewalk), infiltration trenches (IT), and underground detention basins (DB). These SCMs, namely, PW, GS, IT, and DB, are assigned the index j = 1, 2, 3, and 4 respectively. For design purposes, the 2400 m Glenoaks boulevard is divided into eight 300-m long segments. Each 300-m segment is considered as a "site", therefore, i =1, 2, …, 8.

Figure 5.5 depicts the stormwater volumes (I_i = 1688 m^3) and suspended sediment concentrations (C_i = 100 g/m^3) accruing to each site on the Glenoaks boulevard, and the potential locations of the SCMs sites on or near the boulevard. Table 5.1 lists data on SCMs for the example. The data on Table 5.1 indicate that the SCM have standardized designs. Thus, the percolation wells have diameters equal to 1 m. Their unknown dimension is their length (depth). Grassy swales have a length of 300 m and a depth of 0.46 m, their unknown dimension being their width. The infiltration trenches are 300 m with depth of 1 m, their unknown dimension being their width. Each detention basin is 20 m long by 15 m wide, their unknown dimension being their depth.

The treatment efficiencies for suspended solids (ξ) listed in Table 5.1 represent average values over the service life of the SCMs. In actuality, those efficiencies tend to be above average at the beginning of the service life of the SCMs and decline over time until maintenance or replacement is effected on them.

5.6.2 Hydrologic and Hydraulic Properties of the Nonlinear Programming SCMs

The retention coefficients of a SCM, a_{ij} and c_{ij}, and its flow-through coefficients, $b_{ij}$and d_{ij}, determine the stormwater retention and flow-through volumes that can be achieved at each SCM and deployment site. Those coefficients depend on the geometry of the SCM, on its outflow design characteristics, on the infiltration capacity of the surrounding soils, and on the duration of the design storm (48 hours in this case). The volume retention and flow-through coefficients for the SCMs considered in this work (percolation wells, grassy swales, infiltration trenches, and detention basins) are shown on Table 5.2.

5.6.3 Implemented Optimization Model and Constraints

The NLP model given by equations (5.1), (5.2), (5.3), (5.4), (5.5), (5.6), (5.10), and (5.18) was implemented with a maximum budget B = $ 3.2 million (see budget constraint equation (5.5)). Of the optional volumetric constraints, only a constraint on total inflow arriving at the downstream monitoring station (MS) was required, stating that at least 75% of the total storm runoff generated by the design storm in the study area (or 0.75 x 13,504 = 10,128 m^3) must be retained by the SCMs. This is equivalent to requiring that the total volume of stormwater arriving at the downstream monitoring station (Q) must not exceed 25% of the total storm runoff, or $Q \leq 3376\ m^3$ (see constraint equation (5.10)). The water quality constraint requires the stormwater arriving at the downstream monitoring station must have a suspended sediment concentration of at most 50% of that present in the stormwater arriving to the Glenoaks Boulevard, that is, the concentration of suspended solids at the downstream monitoring station may not exceed 50 g/m^3.

5.7 Results and Discussion

5.7.1 Optimal Selection and Size of Nonlinear Programming SCMs

The Nonlinear Programming was implemented with the data, objective function, and constraints specified above. The model was coded in an EXCEL spreadsheet and solved with the software SOLVER available in EXCEL. The optimal combination of SCMs is as follows: site 1: 2 percolation wells, 20 m deep each (1-m diameter by specification); sites 2 through 8: 2 grassy swales per site, each with width equal to 1.95 m (300 m long, 0.46 m deep, by specification). The optimal SCMs meet the capacity or size constraints equation (5.4), with maxima and minima given in Table 5.1. Recall that the depth of percolation wells may not exceed 20 m, and the width of grassy wells is limited to 2 m (see Table 5.1). The cost of the 2 percolation wells on site 1 amounts to \$ 32,200. These 2 wells retain 156 m^3. Each set of two grassy swales (per 300 m of boulevard) on sites 2 through 8 equaled \$ 451,593. Each set of grassy swales retained 1,428 m^3.

5.7.2 Overall Performance Variables

The overall performance variables are as follows: total cost of SCMs: \$ 3.19 million dollars, which complies with the maximum budget equal to \$ 3.2 million; volume of stormwater at the downstream monitoring station: 3,352 m^3 ($\cong$ 25% of the total storm runoff generated by the design storm in the study area, the maximum permissible); suspended-solids concentration at the downstream monitoring station: 49 g/m^3, which is less than the maximum 50 g/m^3.

Stormwater quality was measured downstream of newly installed percolation wells and grassy swales on the Glenoaks boulevard following storm events. It was found that the suspended solids removal efficiencies exceeded 90% in all tested stormwater samples. The observed removal efficiency for new SCMs exceeds their average removal efficiency over their service lives shown in Table 5.1.

5.8 Nonlinear Programming Conclusion

The previous example has demonstrated the usefulness of the NLP method in selecting and sizing SCMs. The selected and sized SCMs optimize cost and efficiency, and meet desired regulatory criteria. The NLP method chooses SCMs that retain required volumes of stormwater by seepage into permeable soils, taking into consideration their cost-wise competitive advantage, as demonstrated in this research case study. Equally important is the fact that the NLP method, once coded, can be used to explore multiple configurations of SCMs, and used to conduct sensitivity analyses that explore the consequences in SCM selection and sizing as costs, pollutants' concentrations, treatment efficiencies, and other variables change. The NLP method keeps theoretical complexities at a minimum, while adhering to physical plausibility. The proposed optimization method for SCM selection and sizing can be solved with ubiquitous software without requiring advanced training in operations research by those concerned with controlling the quantity and quality of urban stormwater.

5.9 Hydrologic and Hydraulic Characteristics of Selected for Nonlinear Programming SCMs

5.9.1 Infiltration Trenches and Grassy Swales

The retention coefficients of a stormwater control measure (SCM), a_{ij} and c_{ij}, and its flow-through coefficients, $b_{ij}$and d_{ij}, determine the stormwater retention and flow-through volumes that can be achieved at each SCM and deployment site. Those coefficients depend on the geometry of the SCM, on its outflow design characteristics, and on the infiltration capacity of the surround soils. Figure 5.6 depicts a diagram that applies to an infiltration trench or a grassy swale. The infiltration swale is placed underground covered by permeable material, whereas the grassy swale is vegetated with an exposed top surface.

Infiltration trenches are built under sidewalks (parkways) and streets with light traffic. They are covered with porous pavement or other porous cover. Grassy swales are constructed on sidewalks. Stormwater infiltrates through the porous cover (infiltration surface) or vegetated surface (grassy swale) and enters a bed of uniform depth H_{ij}, unknown width W_{ij}, and length L_{ij}, as shown on Figure 5.6. The width W_{ij} and length L_{ij} of the SCM (infiltration trench or grassy swale) are limited by the width and length of the porous pavement. Its depth H_{ij} varies between a half meter and one meter. L_{ij} = 300 and H_{ij} = 1 m for infiltration trenches, and L_{ij} = 300 and H_{ij} = 0.46 m for grassy swales in this study. An outflow pipe is placed in the SCM with its centerline at depth D_{ij} below the porous pavement. The SCM saturates with stormwater during a design storm, and water leaks to the underlying soil as vertical percolation through its bottom area (equal to W_{ij} x L_{ij}). Assume *f* is the infiltration rate in m/hr through the soil beneath the SCM; Δt equals the duration of the design storm. The volume of water retained by the SCM, V_{Rij}, is given by the following expression:

$$V_{Rij} = f_i \cdot \Delta t \cdot L_{ij} \cdot W_{ij} = a_{ij} W_{ij} \tag{5.19}$$

The infiltration rate in our case study is *f* = 0.0254 m/hr, Δt = 48 hours, and L_{ij} = 300 m then a_{ij} = 366 m^2 for infiltration trenches, and a_{ij}= 366 x 2 = 732 m^2 for grassy swales. Notice that there are two grassy swales, one on each sidewalk. Eqution (5.19) is written in terms of the unknown width W_{ij}.The pore space within the SCM is not considered as retention volume because water that saturates that space is assumed to infiltrate during the storm, and it is, therefore accounted for by the volume given in equation (5.19). The retention coefficient c_{ij} = 0 for infiltration trenches and grassy swales.

The flow-through volume (V_{Tij}) of the SCM is carried by the outflow pipe to daylight at a downstream point. The mechanism of water release from the SCM is that of a linear reservoir of effective volume V_{ij} whose change in volume ΔV_{ij} by water release equals (Loáiciga et al., 2014):

$$\frac{\Delta V_{ij}}{\Delta t} = k_{ij}\, V_{ij} \tag{5.20}$$

where k_{ij} is the linear-reservoir coefficient, whose dimensions are inverse time. This coefficient is determined experimentally. The linear-reservoir approximation to releases from hydrologic bodies (such as runoff-retaining SCMs) is widely used in hydrologic analysis, see for example the Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HEC, 2000). Therefore, $V_{Tij} = \Delta V_{ij} = \Delta t \cdot k_{ij}\, V_{ij}$. The effective volume V_{ij} = $D_{ij} \cdot L_{ij} \cdot W_{ij} \cdot v_{ij}$ where v_{ij} symbolizes the porosity of the gravel within the infiltration trench. The flow-through volume assumes the following form:

$$V_{Tij} = \Delta t \cdot k_{ij} \cdot D_{ij} \cdot L_{ij} \cdot v_{ij} \cdot W_{ij} = b_{ij} \cdot W_{ij} \tag{5.21}$$

where $b_{ij} = \Delta t \cdot k_{ij} \cdot D_{ij} \cdot L_{ij} \cdot v_{ij}$. Given that Δt = 48 hours, D_{ij} = 1 m, L_{ij} = 300 m, k_{ij} = 0.0208 hr^{-1}, $\cdot\, D_{ij}$ = 1 m; v_{ij}= 0.40, then $b_{ij} \cong$ 120 m^2 for infiltration trenches. For grassy swales D_{ij} = 0.45 m, and there are two of them, therefore $b_{ij} \cong$ 110.4 m^2 The coefficient d_{ij} = 0 for both SCMs in this instance.

5.9.2 Percolation Wells

A simplified schematic of a percolation well is shown on Figure 5.7. A percolation well retains water by releasing water to the surrounding soil through its lateral surface area and through its bottom area. The bottom of the dry well must be above the highest possible level of the phreatic surface. Let f denote the infiltration rate in the soil surrounding the percolation well, Δt the duration of the design storm, ϕ the well diameter, D the depth of the outlet pipe that releases the flow-through volume from the percolation well, L the unknown active length of the percolation well (this is the length of the well filled with gravel of porosity v), I the stormwater volume that flows into the well. The volume of runoff retained by the percolation well is:

$$V_R = \pi \cdot \phi \cdot L \cdot f \cdot \Delta t + \frac{\pi \phi^2}{4} f \cdot \Delta t \quad (5.22)$$

Equation (5.22) is rewritten in the standard form as a function of the unknown well length L:

$$V_R = a \cdot L + c \quad (5.23)$$

in which:

$$a = \pi \cdot \phi \cdot f \cdot \Delta t \quad (5.24)$$

and:

$$c = \frac{\pi \phi^2}{4} f \cdot \Delta t \quad (5.25)$$

Recall there are two percolation wells per site on the boulevard (the two wells considered as one unit). Letting f = 0.0254 m/hr, Δt = 48 hours, ϕ =1 m, produces a = 2 x 3.83 = 7.65 m^2, c = 2 x 0.96 = 1.92 m^3.

The flow-through volume in a percolation well is modeled as the release of a linear reservoir whose volume is in this instance equal to the effective well volume located above the outlet pipe. Therefore:

$$V_T = D \cdot \frac{\pi\,\phi^2}{4} \cdot v \cdot k \cdot \Delta t = d \tag{5.26}$$

Notice that in this case V_T is independent of the decision variable, L, therefore, $b = 0$. Setting $D = 1$ m, $\Delta t = 48$ hours, $\phi = 1$ m, v (porosity) = 0.40, and $k = 1$ hr^{-1}, and recalling that there are two percolation wells on each site (considered as one unit) yields $d = 2 \times 15.1 = 30.2$ m^3.

5.9.3 Detention Basins

Refer to Figure 5.8 for a schematic of a detention basin. The volume retained equals the storage capacity of the basin:

$$V_R = L \cdot W \cdot H = 20 \cdot 15 \cdot H \tag{5.27}$$

Detention basins are built in this case with impervious walls and bottoms, and, so that $a = 300$ m^2, and $c = 0$.

The flow-through volume equals:

$$V_T = k \cdot \Delta t \cdot D \cdot L \cdot W = d \tag{5.28}$$

V_T is independent of the design variable H. With $k = 0.0417$ hr^{-1}, $\Delta t = 48$ hr, $D = 2$ m, $L = 20$ m, and $W = 15$ m, then $d = 1200$ m^3, and $b = 0$. This completes the hydrologic and hydraulic analysis of the pertinent NLP for SCMs.

Table 5.1. SCM generic data (ξ denotes the treatment efficiency of SCMs for suspended solids)

SCM	Total unit cost [(1)]	K_{max}	K_{min}	ξ
Percolation wells (PW, j=1)[(2)]	\$ 1,610/ m	20 m (depth)	10 m (depth)	0.75
Grassy swales (GS, j=2)[(3)]	\$ 231,586/m	2 m (width)	1 m (width)	0.85
Infiltration trench (IT, j=3)[(4)]	\$ 139,800/m	4 m (width)	2 m (width)	0.85
Detention basin (DB, j=4)[(5)]	\$ 349,500/m	8 m (depth)	4 m (depth)	0.75

[(1)]The sum of variable cost plus fixed cost equal to 10% of variable cost, per site; [(2)]well diameter = 1 m; [(3)]length = 300 m, depth = 0.46 m; [(4)]length = 300, depth = 1 m; [(5)]length = 20 m, width = 15 m. Each site may have 2 PWs or 2 GSs (reflected in their total unit cost), or either one IT or one DB.

Table 5.2. Hydrologic and hydraulic data for SCMS and sites i = 1, 2, …, 8.

SCM	a_{ij} (m^2)	c_{ij} (m^3)	b_{ij} (m^2)	d_{ij} (m^3)	I_i (m^3)	C_i (g/m^3)	R_i (m^3)	CU_i (g/m^3)
Percolation wells (PW)	7.66[(1)]	1.92[(1)]	0[(1)]	30.2[(1)]	1688	100	0	0
Grassy swales (GS)	732[(2)]	0[(2)]	110.4[(2)]	0[(2)]	1688	100	0	0
Infiltration trench (IT)	366	0	120	0	1688	100	0	0
Detention basin (DB)	300	0	0	1200	1688	100	0	0

[(1)]2 PW per site; [(2)]2 GS per site.

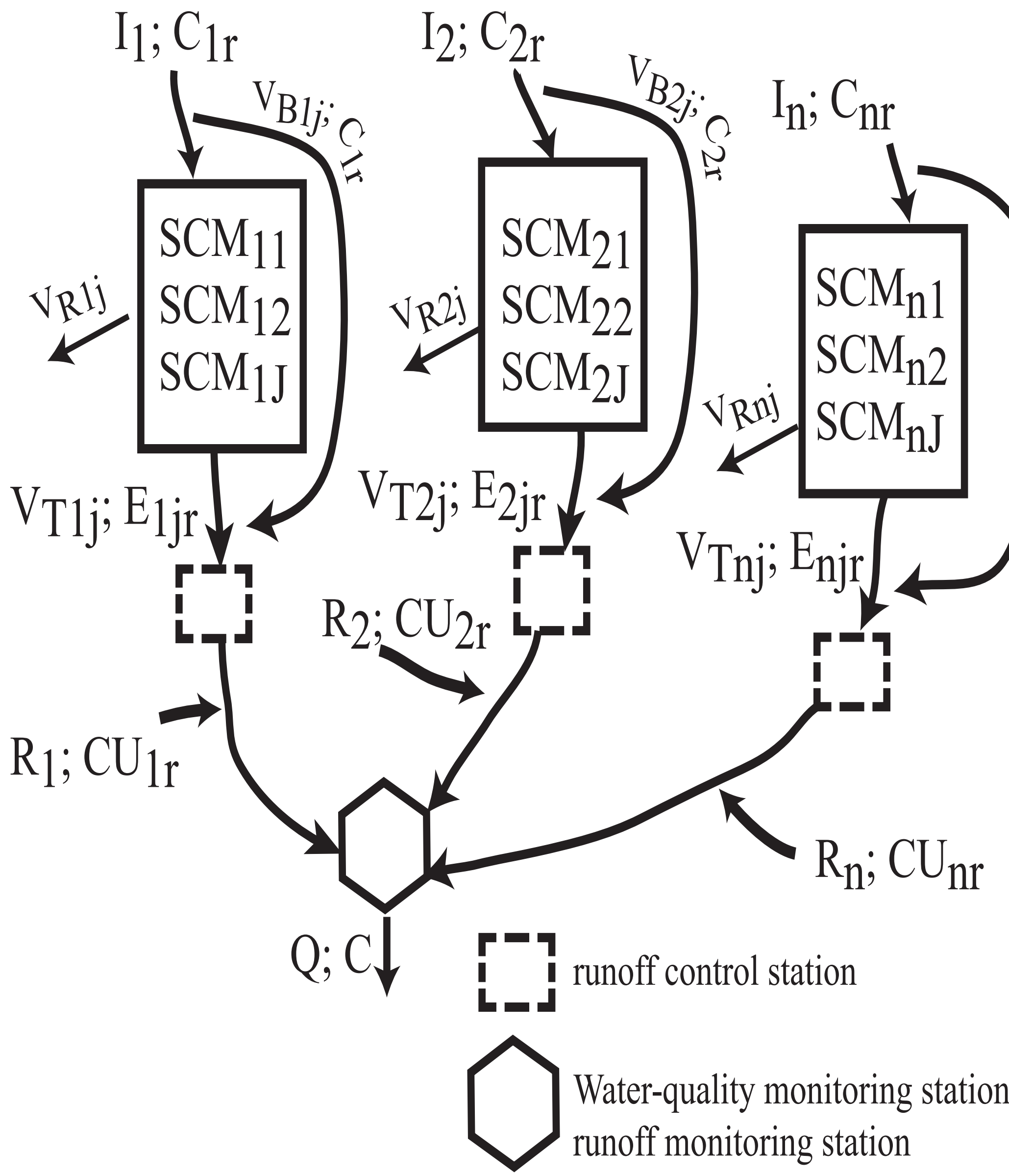

Figure 5.1. Schematic of SCMs configuration and other physical features. Plan view not drawn to scale.

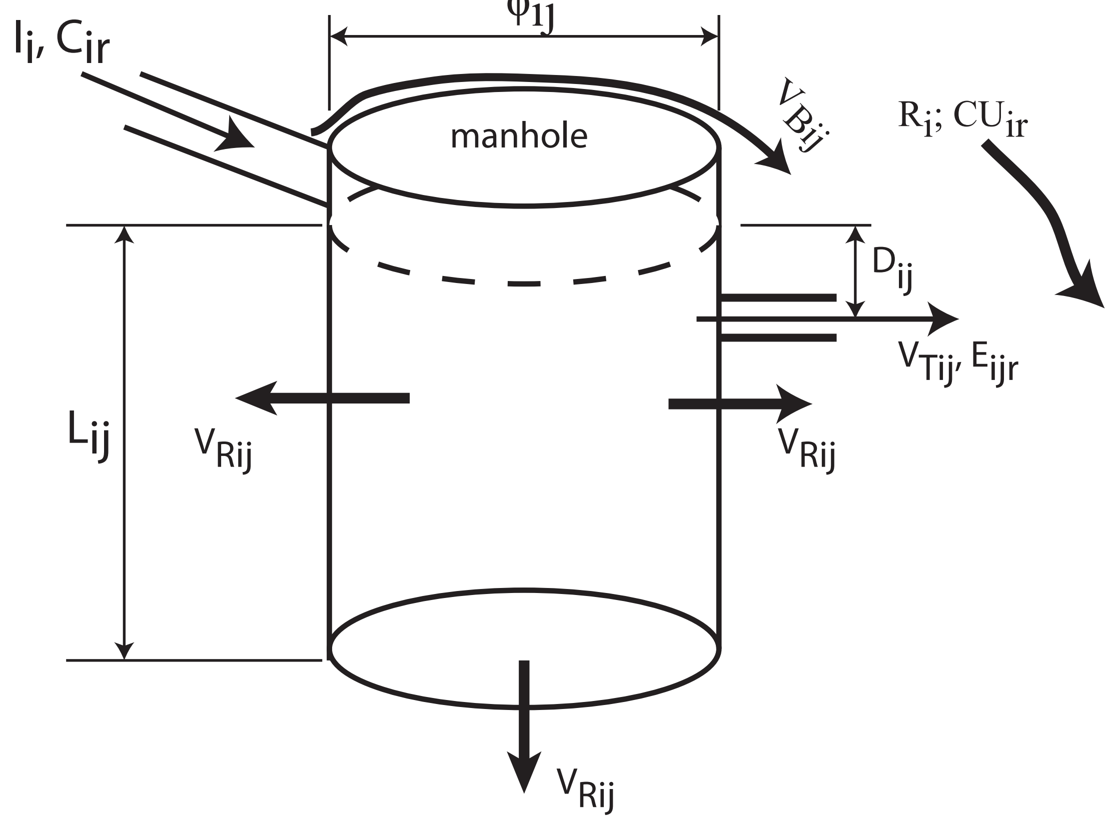

Figure 5.2. Percolation well and typical fluxes in SCMs. Elevation view not drawn to scale.

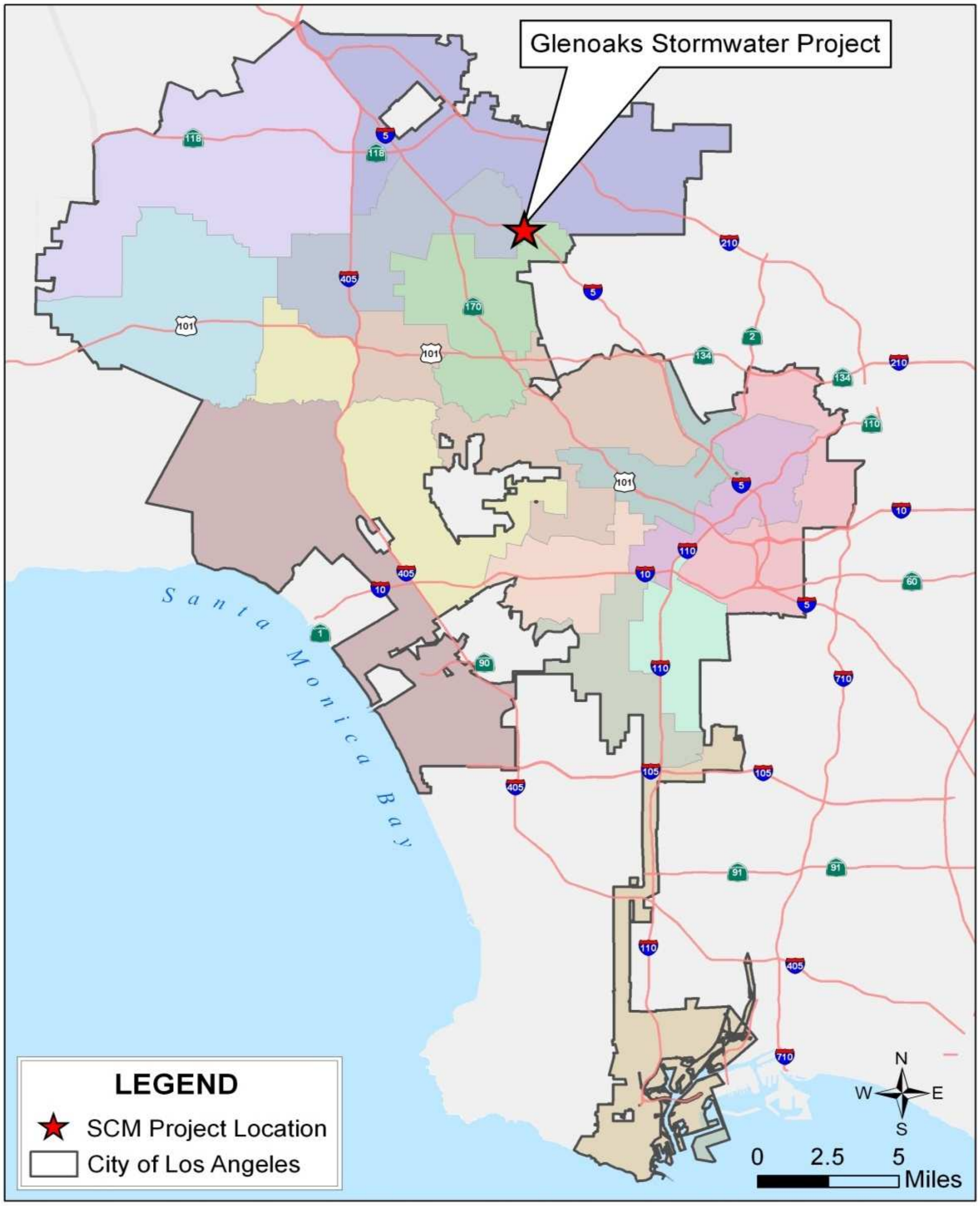

Figure 5.3. The City of Los Angeles Glenoaks stormwater capture project. Colored areas depict the 15 City Council districts within the City of Los Angeles.

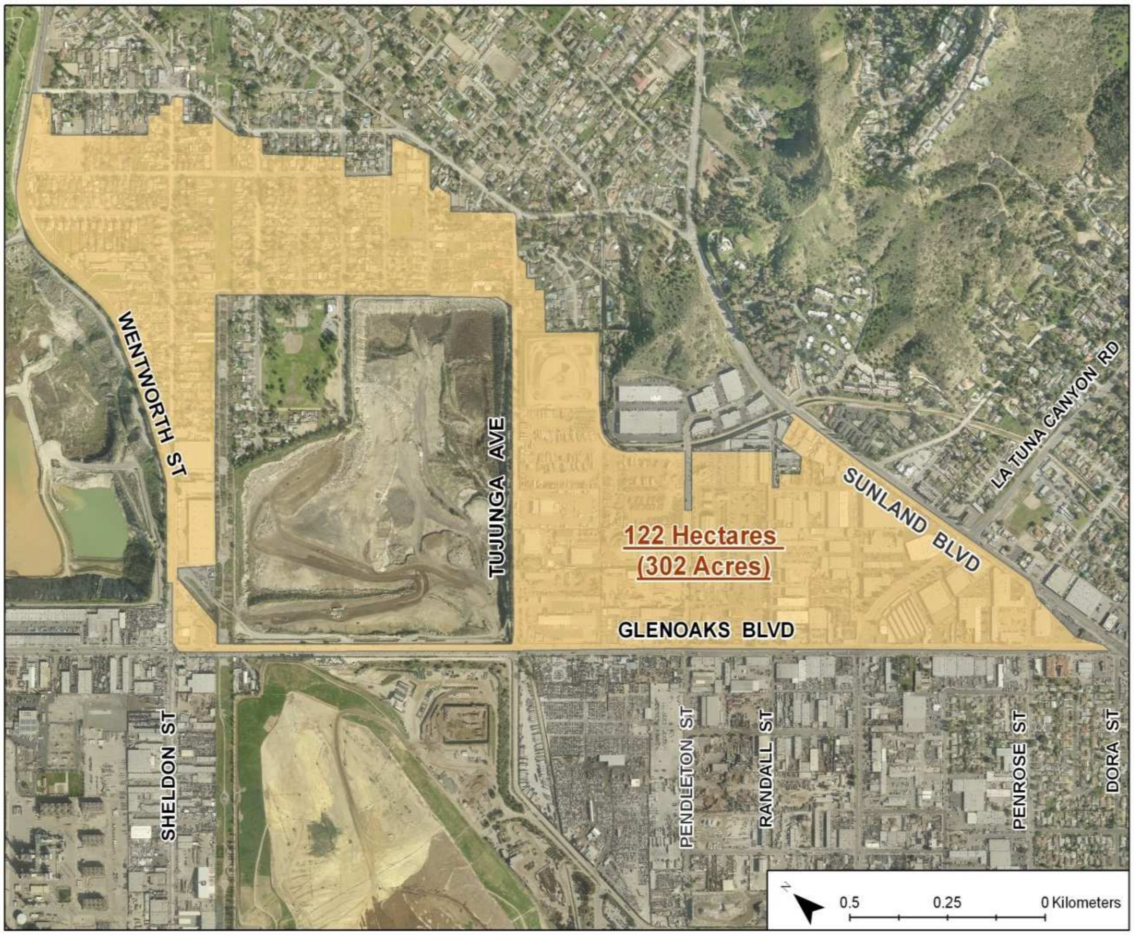

Figure 5.4. The Glenoaks stormwater drainage area (light-brown colored) and the Glenoaks boulevard.

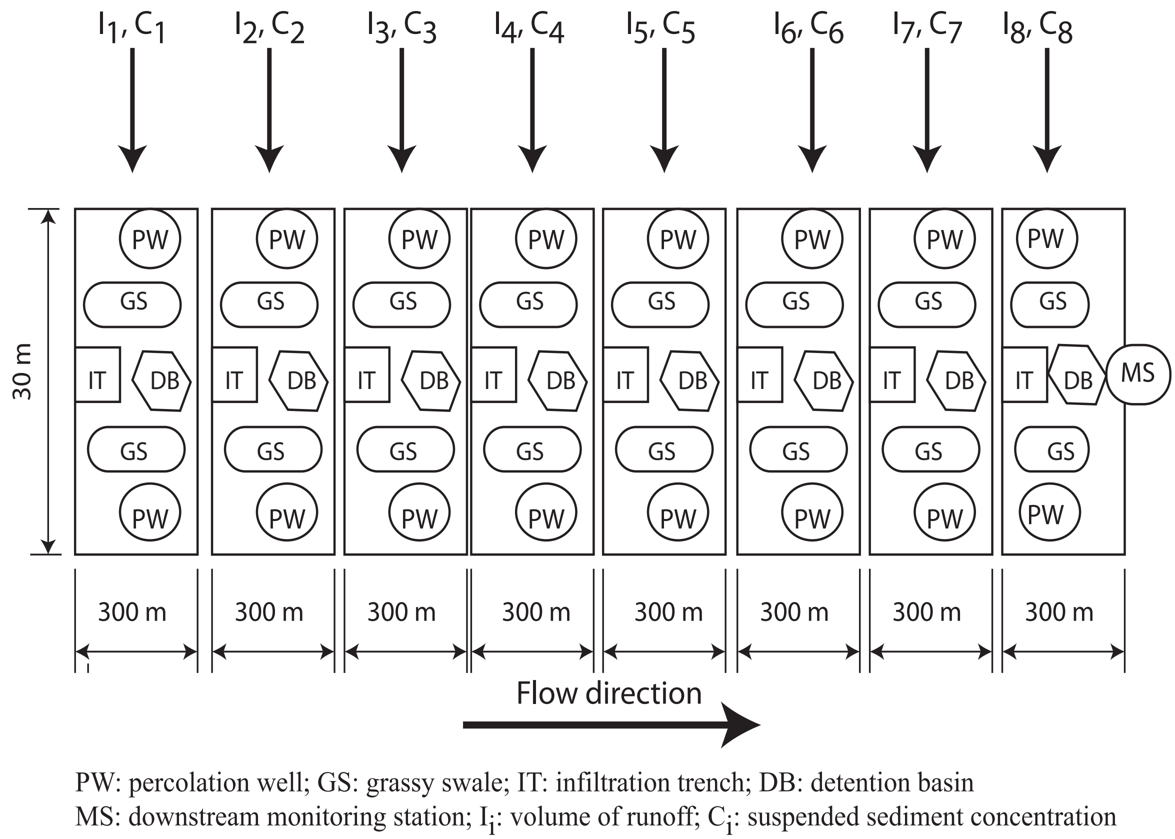

Figure 5.5. Schematic (not drawn to scale) of the Glenoaks boulevard with its 8 sites, each 300 m long, and possible SCMs to be deployed at each site.

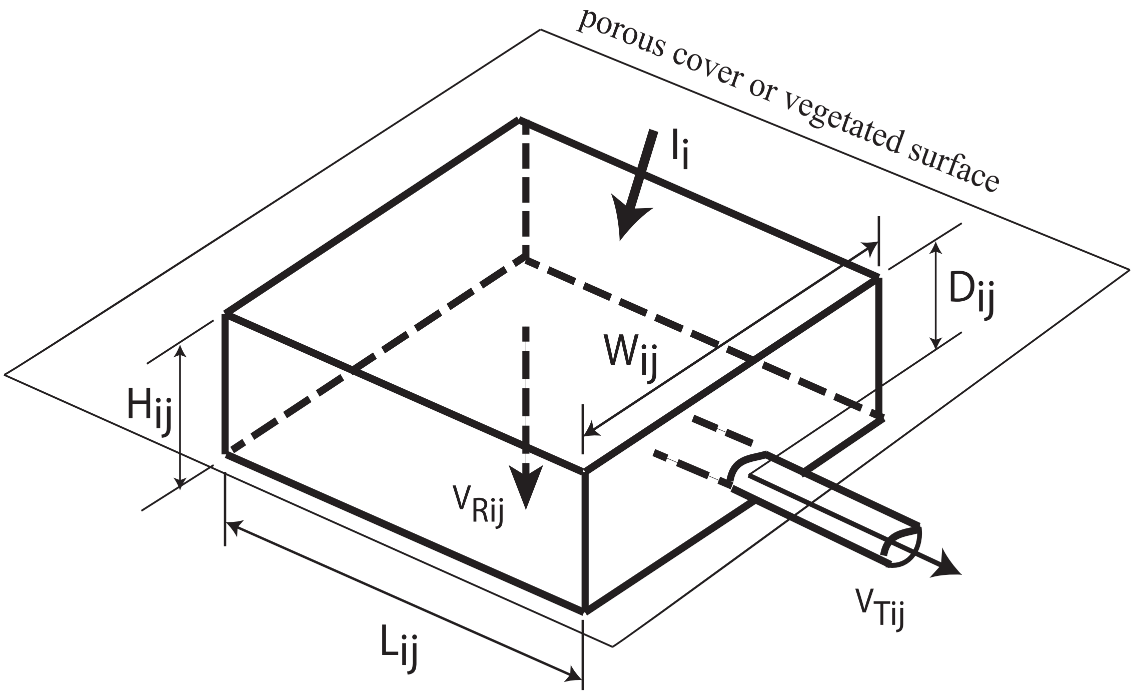

Figure 5.6. A typical infiltration trench or grassy swale.

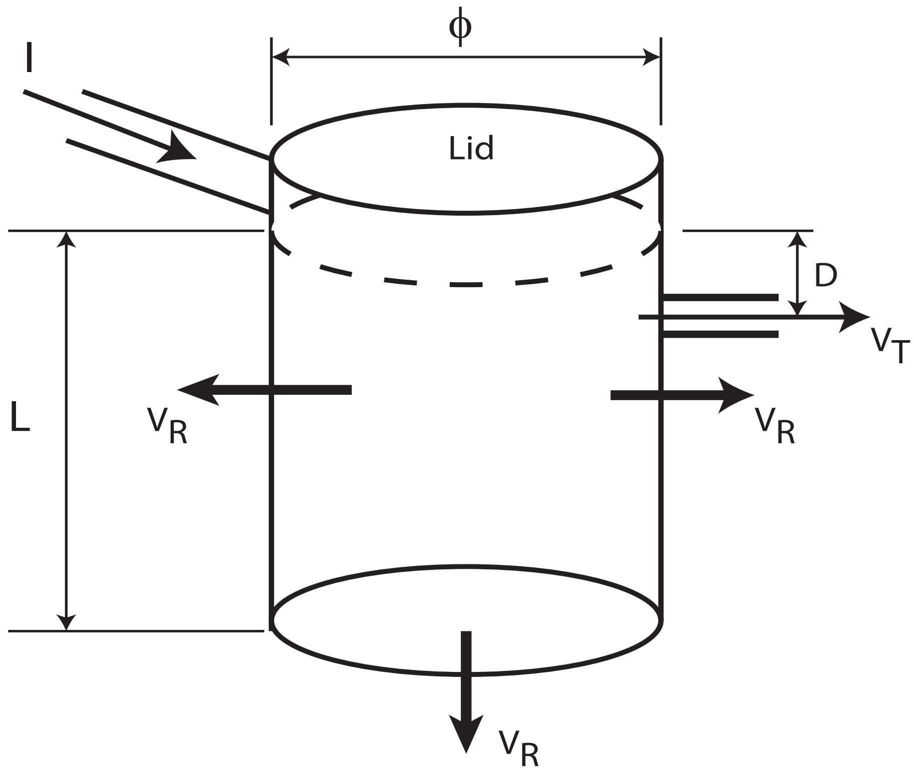

Figure 5.7. Percolation well and main intervening variables. Elevation view.

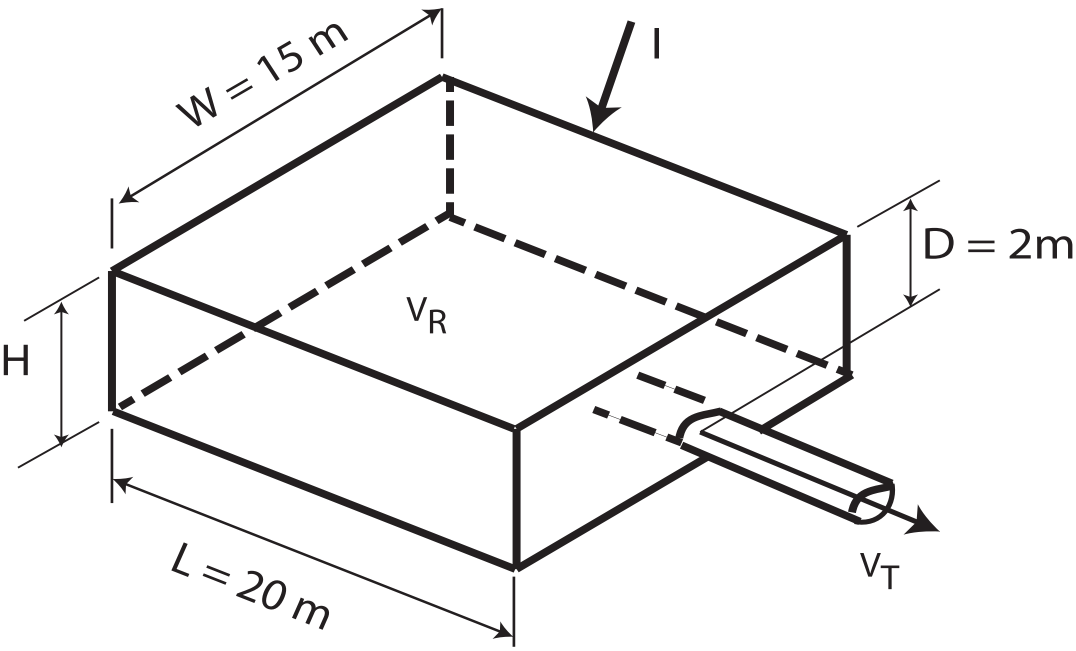

Figure 5.8. Schematic of a detention basin.

6. EXPERIMENTAL RESULTS OF SCMS PERFORMANCE

6.1 Observational Study

6.1.2 Observational Study of Selected Storage/Infiltration SCMs Performance with Controlled Conditions

This research study has gathered observational data on SCM performance at the local scale with controlled conditions. To this end an observational (experimental) study has been carried out involving the design, construction, and performance analysis of dry wells and infiltration swales. Other SCMs studies are being reviewed and will be published in the near future. The purpose is to monitor pollutants' concentrations (bacteria, heavy metals, nutrients, and TSS, cited earlier) in incoming storm runoff to dry wells, infiltration swales, etc and in the outgoing subsurface flow from these SCMs. The incoming versus outgoing water-quality characteristics establish the effectiveness of each BMP in removing pollutants. Figures 6.1 and 6.2 illustrate generic diagrams of dry wells and vegetated infiltration swale, respectively. All the site locations for possible SCM deployment for this observational study were thoroughly characterized hydrogeologically and geotechnically to ensure proper soil, phreatic surface, and liquefaction hazard conditions.

Figure 6.3 depicts the subject area in which the location will be the test area. The map is in the North part of Los Angeles (Glenoaks/Sunland Stormwater Capture Project). The area has acreage of 122 hectares (302 acres) drainage area. The location of SCMs considered soil type, depth to groundwater, pollutant loads (Figure 6.3 shows the three conditions). Priority was given to infiltration/storage SCMs whenever physical conditions permit. An analysis of the study site revealed sandy loam with infiltration rate equal to 1.0

in/hr. A regulatory requirement is that the soil have at least 0.5 in/hr infiltration rate, thus making the sandy soil suitable for the deployment of dry wells and grassy swales. Only a grassy swale with a liner and under drain pipes was used at sites with infiltration rates equal to 0.5 in/hr or lower. The project was finished in June 2013 with a total budget of $509,000.   A total of four dry wells and six grassy swales were installed at this location in the Glenoaks project.

6.1.3 Results for Glenoaks Stormwater Capture Project North part of Los Angeles

The SCMs designs used for the Glenoaks project site location were the Standard Plans developed by City of Los Angeles LA Sanitation/Bureau of Engineering for the grassy swales (City of Los Angeles 2010). The Standard Plans used for this site is shown in Figure 6.4. The dry wells are now pending approval for City of Los Angeles Standard Plans and are shown in Figure 6.5. These two SCMs were used for the site at Glenoaks project.

The Glenoaks project site location was analyzed for the volume of runoff. The 302 acres has about 60% impervious land and about 40% pervious by the land use in the Sun Valley area in Northern Los Angeles. From using the Standard Urban Stormwater Migration Plan (SUSMP) calculations of 0.75" runoff we have about 50.6 cfs runoff and 476,873 ft^3 (3,567,010 gallons) [13,483,309 liters] of stormwater (City of Los Angeles, 2009E).

At this site no dry weather storm event was observed and therefore no samples were collected (several site visits were attempted with no stormwater results). Sampling of the wet weather storm events at North Los Angles locations met the following criteria: (1) forecasted rainfall was greater than or equal to 0.1 inch; and (2) the onset of rainfall was preceded by at least 72 hours of dry weather. Table 6.1 lists a summary of average percent removal of pollutants. Samples for one storm events were collected at two different locations of the installed dry wells and grassy swales on November 11, 2013. For the rain event on November 11, 2013 the total amount stormwater infiltrated from the four dry wells was approximately 1 ac-ft (from the reading of the flow meter at one of the inlet of the dry wells). Trash and debris were also monitored for the Project. The amount of trash and sediments in the primary chamber was about seven (7) cubic feet at a dry well and about five (5) cubic feet, respectively. A total of 12 cubic feet of trash and debris removed was removed. As the results show the dry wells are capturing the stormwater flow and infiltrating into the soil. It has been determined from field data that the pollutant loads are somewhat higher during rainfall events following long periods of dry weather, the so-called "First Flush Phenomenon (Stenstrom and Kayhanian, 2005).

6.2 Photographs of the Sites at the Glen Oaks-Sunland Project

6.2.2 Construction Photograph Taken May 2013

Photo of the excavation of the grassy swales.

Pouring the concrete for the dry wells and catch basin site.

6.2.3 Post Construction Photograph Taken June 2013

Photo of the finished grassy swales .

Photo of the grassy swales under construction.

Photo of a finished dry well’s secondary chamber.

Photo of the piping for the flow meter between the primary chamber and the secondary chambers used to calculate the stormwater flow into the dry wells.

Photo of the flow meter used to calculate the stormwater flow into the dry wells.

6.2.4 Photos Taken on November 2013 Sampling During Rain Event

Photo of a grassy swale during a sampling event.

Photo of a grassy swale during a sampling event.

Photo of a catch basin during a sampling event before entering the dry wells.

Photo a dry well's primary chamber after a storm event.

Photo of a dry well’s secondary chamber during storm event.

Table 6.1. Summary of Average Concentrations of Inlet and Percent Removal of Pollutants for Subject area (samples taken November 2013)

Pollutant	**Unit**	**Average Concentrations for Inlet Wet Weather Samples**
E. Coli	MPN/100mL	**15,650**
Enterococcus	MPN/100mL	**46,150**
Total Coliform	MPN/100mL	**230,000**
Cadmium (Total)	ug/l	**1.4**
Cadmium (Dissolved)	ug/l	**0.3**
Copper (Total)	ug/l	**112**
Copper (Dissolved)	ug/l	**39**
Lead (Total)	ug/l	**42**
Lead (Dissolved)	ug/l	**4**
Selenium (Total)	ug/l	**0.5**
Selenium (Dissolved)	ug/l	**0.3**
Zinc (Total)	ug/l	**604**
Zinc (Dissolved)	ug/l	**175**
Total Suspended Solids	mg/l	**190**

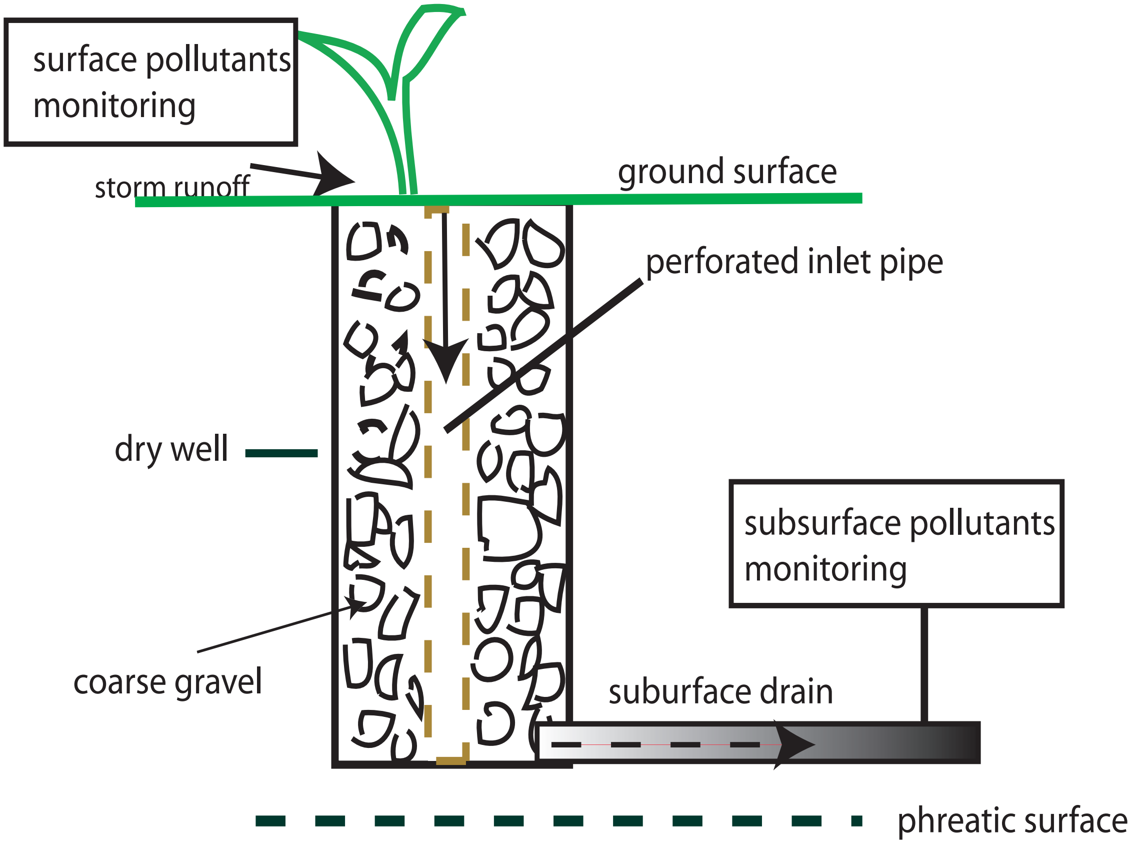

Figure 6.1. Dry well SCM System for the testing of stormwater runoff.

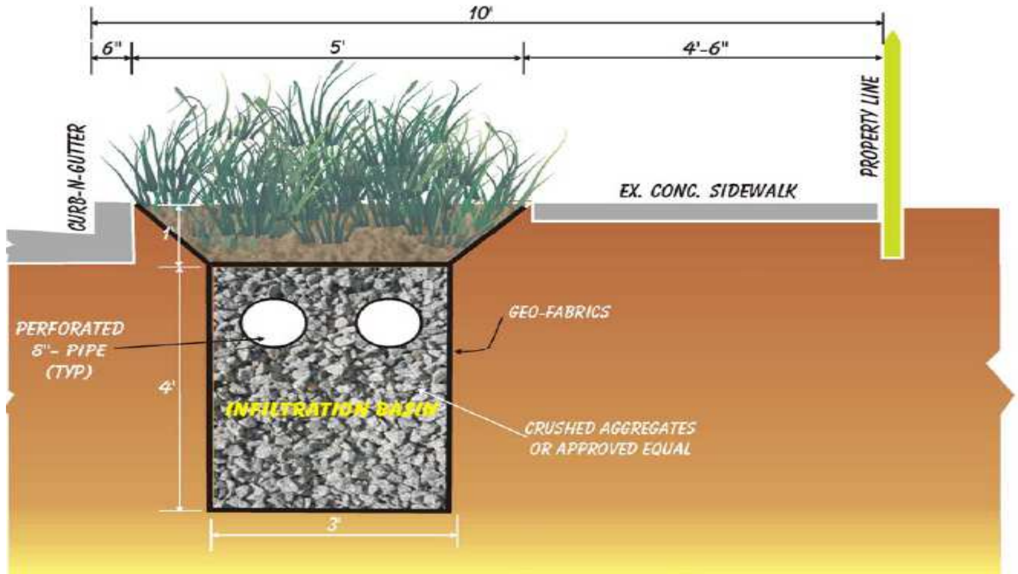

Figure 6.2. Vegetated infiltration swale and the vegetation grow on filter strips that retain fine particles that might clog the swale's pore space.

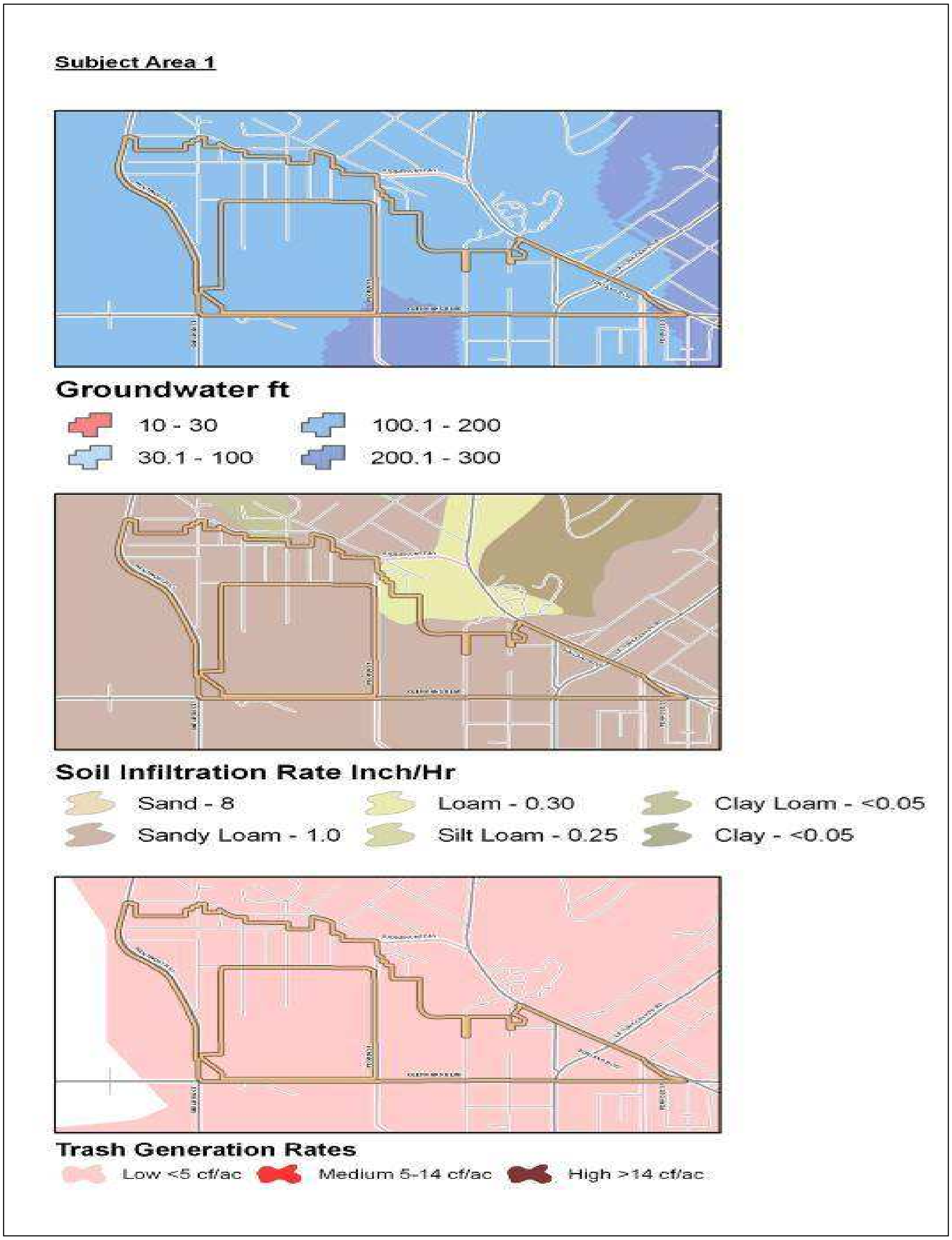

Figure 6.3. The map showing subject area at Glenoaks project (North part of Los Angeles - 302 acres) with groundwater depth, soil infiltration rates, and loading for trash.

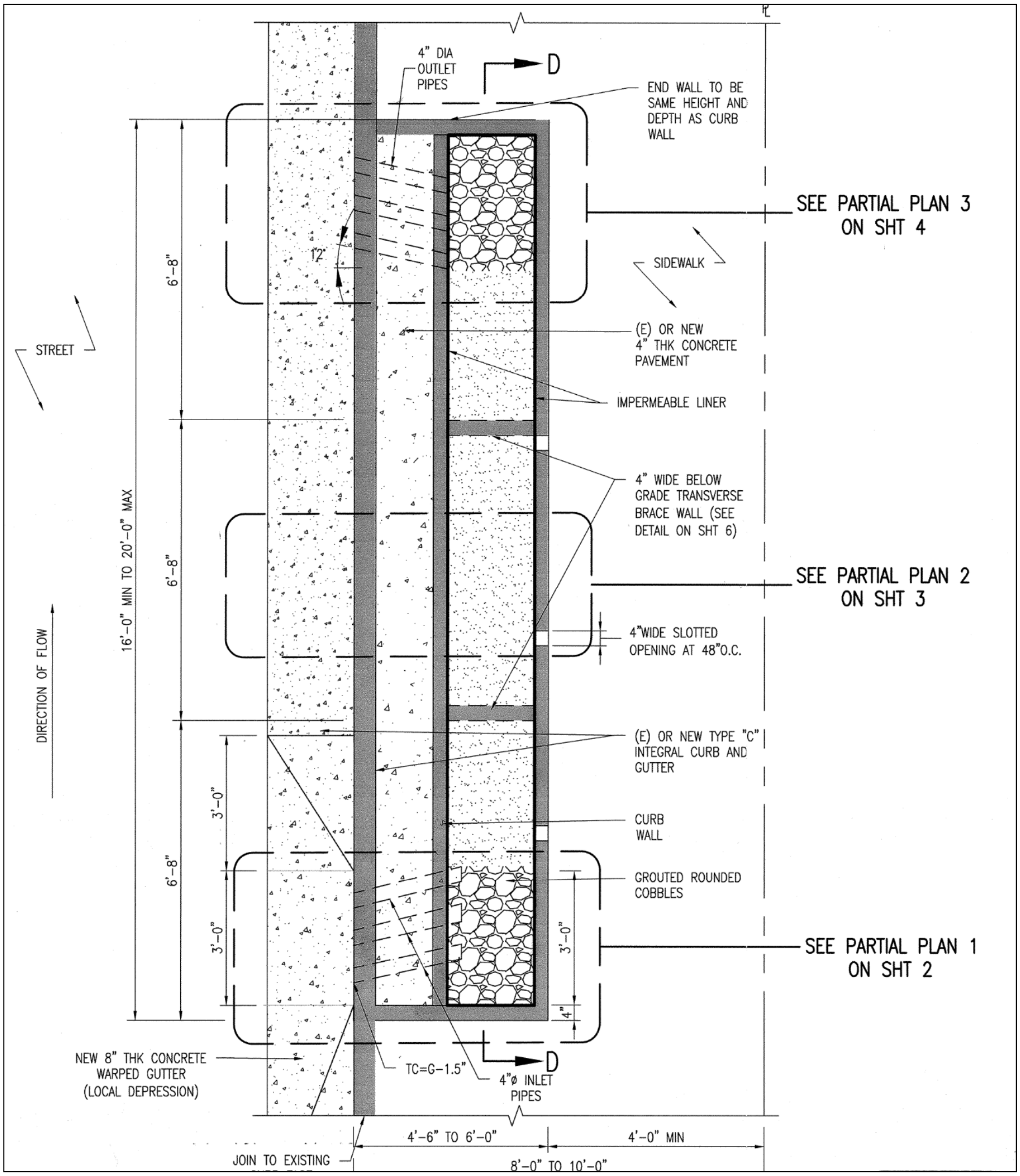

Figure 6.4. Vegetated swale: plan view of SCM Treatment Train for Subject Area in the North Los Angeles. Grassy Swale used for this project site from City of Los Angeles Standard Plans.

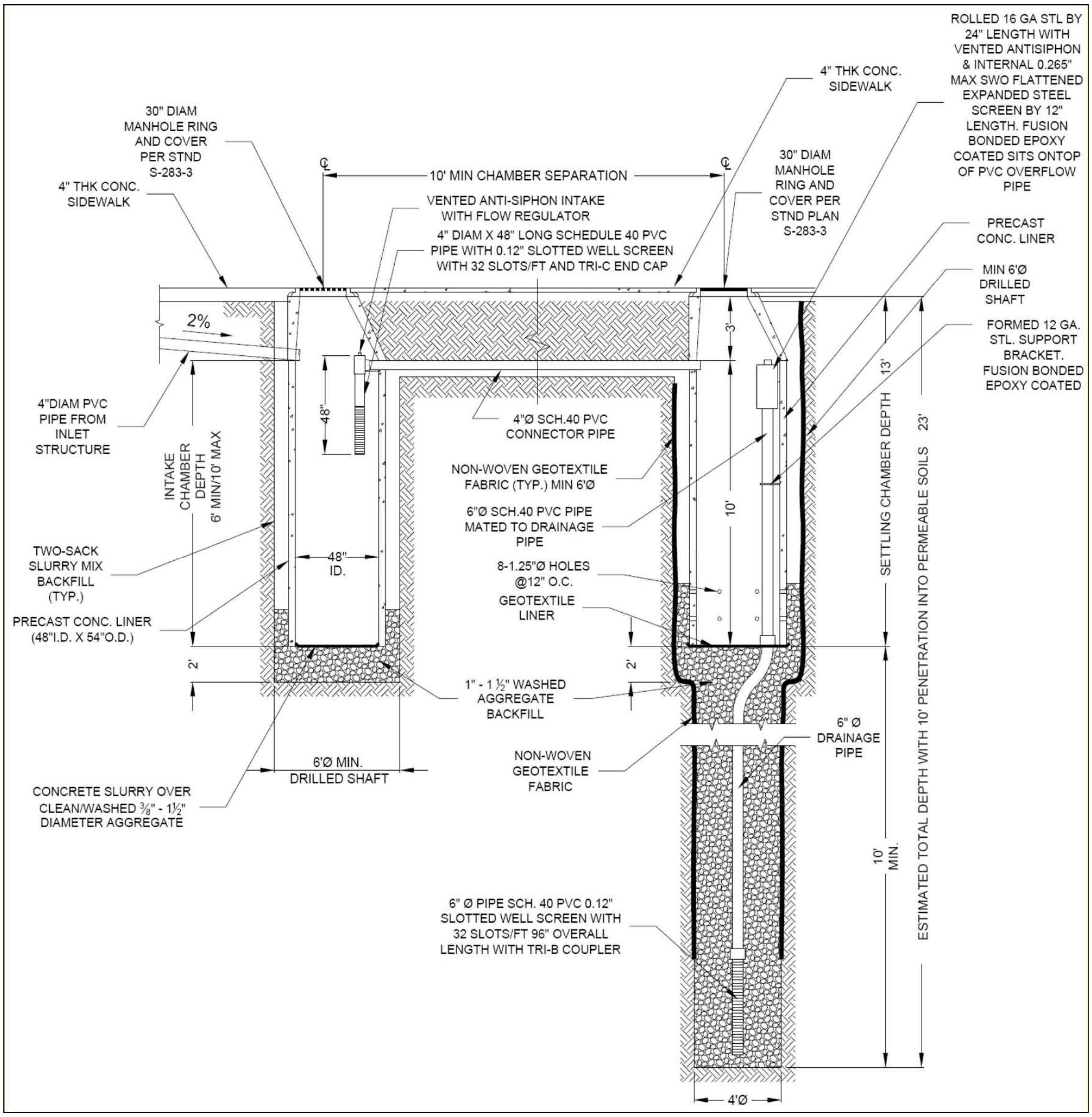

Figure 6.5. Percolation wells: elevation view of SCM Treatment Train for Subject Area in the North Los Angeles. Dry wells from Torrent Resources used for this project site.

7. OUTCOMES OF THE RESEARCH, CONCLUSIONS, AND FUTURE RESEARCH

This dissertation has presented a method for SCM sizing and placement, plus field measurements of stormwater phenomena dealing with stormwater, ways to clean it, and ways to using it to reduce potable water demand and conserve water. This study topic provides answers to the questions on how to capture polluted rainwater in an urbanized setting, improve stormwater quality, and reduce the quantity of stormwater in an effective manner. This research focused on development of a novel approach for SCM sizing and placement, through linear and nonlinear optimization modeling, and to identify high priority catchments with maximum pollutant loads. The optimization model determines proper stormwater control measures (SCMs) that are employed to reduce pollutant concentrations to mitigate the adverse impacts of storm runoff in urban areas everywhere and to meet TMDLs. Optimization methods were developed and presented in this research to minimize the total cost of SCMs deployment while satisfying constraints on (i) the total cost of deployment, (ii) SCM capacities, (iii) volumetric balance at SCM sites, (iv) stormwater volumes at arbitrary sites, (v) unit Operational, Maintenance, and Replacement (OMR) cost, and (vi) water-quality at monitoring locations. The two version of the optimization models are:

- ***Linear Programming (LP)*** for optimal sizing of SCMs relies on a linear programming formulation for sizing SCMs. In addition, the Binary Linear Integer Programming (BLIP) for optimal selection of SCMs based on a binary (0,1) linear integer programming formulation.

- ***Nonlinear Programming (NLP)*** for optimal sizing and selection of SCMs uses mixed (binary-real) nonlinear integer programming formulation.

The LP and NLP methods are generic in their formulations and can be applied to various types of SCMs. An appealing trait of the LP and NLP methods is that globally optimal solutions can be obtained with the SOLVER package in the ubiquitous software EXCEL. This research work presented a methodology aimed at aiding stormwater practitioners with real-world problems. Three examples were presented in this research work to illustrate the application of the LP, BLIP, and NLP methodologies. The three examples were successfully solved after a detailed step-by-step formulation.

This thesis' methodology aims at providing a practical tool for stormwater practitioners with several goals in mind. First, the methodology captures the basic stormwater management objectives, that is, the control of stormwater quantity and quality. Second, the methodology relies on fundamental principles of conservation of mass, cost considerations, and generally available or developable data with which to construct the optimization problems. Lastly, the methodology can be implemented in ubiquitous, widely accessible, software that does not require specialized training in optimization theory by practitioners well versed with SCMs. The previous chapters presented the methodology for SCM optimization and clarify its application with three examples and one field study.

The principal areas of applied optimization research and outcomes of this research are as follows:

- Development of a GIS-based approach to determine priority catchments for stormwater management within a sub-watershed by using SCM-Applicability indices (Geographic Information Systems (GIS) layers).

- Development of a SCM selection module that determines the type of SCMs that are most cost effective in reducing the pollutant loads and concentration in urban runoff; SCM is defined as a device or technique (structural) that is used to remove or reduce pollutants load: SCMs studied in this research are Infiltration Vegetated Swale, Percolation Wells, Catch Basins Filter Screens, and others.
- A nonlinear model herein named Nonlinear Programming (NLP) for SCM sizing and selection whose designs can be field verified with site specific data.
- The monitoring of the water quality has been and will continue to be closely investigated for the designed and implemented SCMs (dry wells, infiltration vegetated swales in the project site).
- The optimization programing method keeps theoretical complexities at a minimum, while adhering to physical plausibility.
- The proposed optimization method for SCM selection and sizing can be solved with ubiquitous software without requiring advanced training in operations research by those concerned with controlling the quantity and quality of urban stormwater.

Concerning **future research work** based on SCM modeling as proposed in this work, several areas of inquiry are identified. These include watershed-scale hydrologic, climatic, water-quality, socio-economic integrative data analyses, with controlled field testing of SCMs with the objective of furthering the sustainability of large urban areas and their impacted environments. The models LP and NLP will change with changing conditions, although those models have built-in flexibility for the user to change parameters and variables as needed without having to re-structure the models as long as they continued to be used as single-event rainstorm design tools. The following are other areas for future research to expand the current work on SCMs accomplished in this thesis:

- Compare the LP and NLP models with other exiting models and identify their limitations and factors;
- Ways to specify budget constraints when working with many different SCMs;
- Consider possible impacts of Climate change on rainfall intensity and stormwater generation in urban areas, and how such changes might the SCM model and its performance;
- Improve ways to quantify pollutant loading for the LP and NLP model;
- Continue the study and application of Low Impact Development (LID) SCMs, such as vegetated swales, green roofs, porous asphalt/concrete, green streets, percolation wells, rainwater harvesting, mulching, tree planting, green infrastructure, and others;
- Further characterization of rainfall events and their patterns and their specification in the LP and NLP model;
- Research statistical methodology for refining rainfall patterns and assessing the potential effect of climate change on storm runoff generation and its pollutants load;
- Refine the Operations, Maintenance, Replacement costs and their effects on the SCMs design models and field testing of their performance;

- Further research applying GIS for more detailed and electronic processing of spatial variables mapped digitally within urban regions (rainfall, soils, groundwater, topography, land use, roads, pollutant sources, storm runoff infrastructure, and others);
- Develop automated decision-making software based on GIS system that relies on digitally-mapped variables to assess the effectiveness, cost, and suitability of potential SCMs and to choose an optimal combination of SCM-technologies for storm-runoff control and treatment;
- Study changing and expanding population and land use within urban areas and their effects on stormwater runoff and pollutant loads;
- Research contamination of water bodies with degraded storm runoff that hinders their hydrologic, ecologic, and socioeconomic functions;
- Study the performance of SCMs in different conditions of variable storm events and possible impacts of climate change;
- Outreach and community involvement for improving SCM effectiveness and social and economic effects in the LP and NLP models for SCM sizing and selection;
- Study the cost of SCMs development and treatment based on State and Federal regulations on total maximum daily loads (TMDLs) of pollutants to natural waters from urban storm runoff;
- Research comprehensive hydrogeologic and geotechnical subsurface characterization at the observational sites for SCMs developments.

All these areas of further research deserve attention and resources to advance the state-of-art on the design, implementation, and management of stormwater treatment technologies.

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Appendix A. Acronyms/Definitions

303(d) list	List of "water quality limited segments" (water bodies) that require TMDLs to satisfy section 303(d) of the Clean Water Act.
Aldrin Compound	Belonging to the group of organochlorine insecticides.
Anthropogenic	Caused by human activity (as opposite to caused by nature).
BMP	Best Management Practice
BOD	Laboratory measurement of the amount of oxygen required by bacteria to consume organic chemicals in water Biological Oxygen Demand (BOD). A BOD usually results in a water body deficient in oxygen and not being able to support higher life forms.
Biofiltration	Instantaneous process of filtration, infiltration, adsorption and biological uptake of contaminants that takes place when stormwater flows over and through vegetated areas.
Bioremediation	Use of living organisms (typically bacteria) to clean up pollutants from soil, water, or wastewater.
Bioretention	Stormwater controls that utilize shallow storage, landscaping and soils to control and treat stormwater by collecting it in shallow areas before filtering it through a planting soil media.
Biosolids	Term used by the water treatment industry which refers to treated sludge.
BLIP	Binary Linear Integer Programming

CBF	Catch Basin with Filter media
CDS	Continuous Deflective Separation
CIP	Capital Improvement Projects
CWA	Clean Water Act
Catch Basins	Storm drain inlet or curb inlet to the storm drain system that characteristically includes a grate or curb inlet where stormwater enters the catch basin and a sump to capture sediment and debris.
Cistern	Reservoir, tank, or container used for storing stormwater in order to enable its use for irrigation or stormwater reuse.
Coliform Bacteria	Class of bacteria that are commonly used as indicator of likely occurrence of pathogenic organisms.
Composting	Controlled biological decomposition of organic material in the occurrence of air to form humus-like material.
Constructed Wetland	The wetlands is created on a site that previously was not a wetlands, specifically to remove pollutants from stormwater.
DB	Detention Basin
DDS	Decision Support System
DDT	Dichloro Diphenyl Trichloroethane

Detention Brief storage of stormwater runoff with the goals of controlling peak discharge rates and providing gravity settling of pollutants.

Disinfection Method in which intolerable micro-organisms are destroyed.

Dry Season Period in which rainfall occurs, in Southern California from April 1st to October 31st.

EPA Environmental Protection Agency

Effluent Discharge of water from a natural body of water, or from a manufactured structure.

Estuary Semi-enclosed coastal body of water with one or more rivers or streams flowing into it, and with a open linking to the sea.

Eutrophication Increase in chemical nutrients. Typically compounds containing nitrogen and phosphorus, in an ecosystem resulting in high primary efficiency.

Enterococcus Group of bacteria used as indicators of water quality for the well-being of public beaches.

GIS Geographic Information Systems (GIS) is tool that links spatial features commonly seen on maps with data from various sources ranging from demographics to pollutant sources.

GS Grassy Swale

GRASS Greenways to Rivers Arterial Stormwater Systems

Greenway Policy	The land use description in land-use planning to retain areas of largely undeveloped, wild, or agricultural land nearby or neighboring urban areas.
Groundwater (GW)	It is water located beneath the ground surface in soil pore spaces and in the fractures of lithologic formations.
Heavy Metals	Metallic elements with relatively high atomic weights (e.g. mercury, chromium, cadmium, arsenic, and lead); can damage living organisms at low concentrations and tend to accumulate in the food chain.
Hydrocarbons	Organic compound consisting entirely of hydrogen and carbon.
Hydrodynamic separator	Engineered structure which separates sediments and oils from stormwater by gravitational separation and/or hydraulic flow.
Hydrograph	Plot of the discharge of a river as a function of time and for surface water hydrology, a hydrograph is a time record of the discharge of a stream, river or watershed outlet.
HEC	Hydrologic Engineering Center
IT	Infiltration Trench
Imp Water Body	Impaired water body that does not meet the standards that supports its designated use.
Impervious	Structures, such as pavement and building roofs, which structures replace natural landscape and prevent stormwater infiltration.

Infiltration	Penetration of water through the ground surface into subsurface soil.
Institutional SCM	Any urban runoff management activity that reduces the generation of pollutants at the source and that does not require engineering and/or construction. Sometimes also referred to as nonstructural or source-control SCMs.
LAMC	Los Angeles Municipal Code's
LID	Low Impact Development
LP	Linear Programming
LA Sanitation	Los Angeles Sanitation (City of Los Angeles)
Lagoons	Body of comparatively shallow salt or brackish water detached from the deeper sea by a shallow or exposed sandbank, coral reef, or comparable feature.
Legacy Toxics	Toxic or hazardous chemicals or residues such as pesticides (DDT for example) and PCBs that are no longer used or their manufacture has been banned but are still present in the environment. These are mostly found in sediments.
Load Allocation	Portion of a receiving water's TMDL that is attributed to one of its existing or future nonpoint sources of pollution or to natural background sources (EPA).
Mg/L	Milligrams per Liter

MNIP Mixed Integer Nonlinear Programming

MPN Most Probable Number

MS Monitoring Station

MS4 Municipal Separate Storm Sewer System for collection of urban runoff, which in the City of Los Angeles is separated from the sewers for collecting sewage.

NLP Nonlinear Programming

NPDES National Pollutant Discharge Elimination System. A provision of the Clean Water Act that prohibits the discharge of pollutants into waters of the United States unless a special permit is issued by EPA, a state, or, where delegated, a tribal government on an Indian reservation.

Nonpoint Source Diffuse pollution source or a source without a single point of origin or not introduced into a receiving stream from a specific outlet. The pollutants are generally carried off the land by stormwater. Common nonpoint sources are agriculture, forestry, urban areas, mining, construction, dams, channels, land disposal, saltwater intrusion, and city streets.

Nonstructural SCM See institutional SCM.

NonVegetative SCM Structural SCM that prevents or reduces pollutants and runoff without utilizing vegetation such as grass, shrubs, and trees.

Nutrient	Chemical compound, usually containing nitrogen or phosphorus, that fuels plant growth.
O & G	Oil and Grease
OMR	Operational, Maintenance, and Replacement
Open Area	Any area that can be used for implementing BMPs without eliminating the primary use. Open area includes open space, privately owned undeveloped land, parks, parking lots, playgrounds and schoolyards.
Open Space	Essentially unimproved land (natural areas) as defined in the California Government Code Section 65560 (b).
Organic Compound	Substance containing mainly carbon, hydrogen, nitrogen, and oxygen.
Organochlorine	Organic pesticides containing chlorine, such as DDT, most of pesticides which are now banned.
PAHs	Polyaromatic hydrocarbons: class of hydrocarbons typically produced by incomplete combustion of organic materials.
PCBs	Polychlorinated biphenyls: group of toxic, persistent chemicals used in electrical transformers and capacitors for insulating purposes, and in gas pipeline systems as lubricant. The sale and new use of PCBs were banned by law in 1979.
PDFS	Probability Density functions

pH	Measure of the acidity (pH less than 7) or alkalinity (pH greater than 7) of a solution.
PW	Percolation Wells
Pathogens	Microorganisms (e.g., bacteria, viruses, or parasites) that can cause disease in humans, animals and plants.
Percolation	Movement and filtering of fluids through porous materials.
Point Source	Stationary location or fixed facility from which pollutants are Discharged. This could be any single distinguishable source of pollution, such as a pipe, ditch, ship, ore pit, or factory smokestack.
Pollutant	Contaminant in a concentration or quantity that adversely changes the physical, chemical, or biological properties of the natural environment.
Pollutant Load	Amount of pollutants in flowing into a water body and the loads are usually expressed in terms of a weight and a time frame, such as pounds per day (lb/d).
Receiving Waters	Creeks, streams, rivers, lakes, estuaries and other bodies of water into which urban runoff flows.
Reclamation Plant	Plant in which raw sewage is treated physically, chemically, and biologically, to become reusable water.
River Reach	Section of the river, often between designated tributaries, that has similar characteristics such as geometry, physical, and width.

Runoff	A term used to describe the flow of water, from rain, snowmelt, or other sources, over the land surface, and is a major component of the water cycle.
SCAG	Southern California Association of Governments
SCM	Structural Control Measures is activity for reducing the amount of pollutants entering a receiving water body from urban runoff and the technique that has been determined to be the most effective/practical means of avoiding/reducing pollution from nonpoint sources.
SS	Suspended solids.
SSO	Sanitary Sewer Overflow: an occasional unintentional discharge of raw sewage from a municipal sanitary sewer.
SUSMP	Standard Urban Stormwater Migration Plan
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
Sand Filter	Device that filters storm water runoff through a sand layer into an underdrain system that conveys the treated runoff to a detention unit or to the ultimate point of discharge.
Sediments	Product of erosion processes, usually small organic and inorganic particles that are transported by flowing water and ultimately settle the bottom.
Semi-Arid	Climatic regions that receive low annual rainfall (250-500 mm or 10-20 in).

Septic Tank Underground storage tank for wastes from homes not connected to a sewer line. Waste goes directly from the home to the tank.

Solid Waste Waste type that includes predominately household or domestic waste with sometimes the addition of commercial wastes collected by a city/county.

Source Control SCM See institutional SCM.

Stakeholder Individual or organization that has an interest in the outcome of the watershed plan.

Stormwater Urban runoff generated by rainfall that does not seep into the earth and flows overland to flowing or open bodies of water.

Stressor Any physical, chemical or biological entity that can induce an adverse response. Stressors cause impairments of water bodies.

Structural SCM Any urban runoff management practice that requires construction, installation, and maintenance (as opposed to institutional SCMs).

Sub-Watershed Smaller basin of a larger drainage area that all drains to a central point of the larger watershed.

TMDL Total Maximum Daily Load: sum of the individual wasteload allocations and load allocations. A margin of safety is included with the two types of allocations so that any additional loading, regardless of source, would not produce a violation of water quality standards (EPA).

TN Total Nitrogen

TSS	Total Suspended Solids: small solid particles that remain in suspension in water as a colloid due to the motion of the water.
Toxicity	Degree to which something is able to produce illness or damage to an exposed organism.
Treatment Control	Structural SCM that focuses on removing pollutants from SCM urban runoff.
Tributary	Stream or river which flows into a main stem (or parent) river, and which does not flow directly into a sea.
USA	United States of America
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
Urban Runoff	Water from city streets and adjacent residential or commercial properties that can transport a range of pollutants. In the dry season, the bulk of the flow is from anthropogenic sources. During wet weather, the flow includes storm generated runoff (stormwater) which can be at much higher volumetric rates.
Vegetative SCM	Structural SCM that reduces pollutants and/or the volume of urban runoff by utilizing vegetation such as ornamental grass, shrubs, and trees. An example is a "vegetative swale" designed to intercept and convey surface stormwater runoff, promote infiltration, interception of sediment by the vegetation and provide a landscape feature in urban areas.

WLA Waste load allocation: the portion of receiving water's total maximum daily load that is allocated to one of its existing or future point sources of pollution (EPA).

WQCMPUR Water Quality Compliance Master Plan for Urban Runoff

Watershed All the land that drains downslope to a common lowest point.

Water Quality Standards

Standards that set the goals, pollution limits, and protection requirements for each water body. These standards are composed of designated (beneficial) uses, numeric and narrative criteria, and anti-degradation policies and procedures.

Watershed Plan Document that provides assessment and management information for a geographically defined watershed, including the analyses, actions, participants, and resources related to development and implementation of the plan.

Wet Season Period in which rainfall occurs, in Southern California from November 1st to March 31st.